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Attention is drawn to the recommendations to authors printed on the inside of the back cover.

Papers offered for publication in the September issue should reach the Assistant Secretary of the Society by mid-May.

Volume 2 No. 2 June 1959

The following contributions have been accepted for publication in the above issue:

N. LANDISMAN, Y. SATO and M. EWING, The distortion of pulse-like earthquake signals by seismographs.

H. TAKEUCHI, Torsional oscillations of the Earth and some related problems.

BRUCE C. HEEZEN, Dynamic processes in abyssal sedimentation; erosion, transportation and redeposition on the deep-sea floor.

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Directions of Rapid Geomagnetic Fluctuations

W. D. Parkinson

(Received 1958 September 29)

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When the geomagnetic field changes, an electromotive force occurs within the Earth. Because the Earth has a finite conductivity, this electromotance gives rise to eddy currents, the magnetic field of which contributes to the total field measured at the Earth's surface.

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All these treatments consider the conductivity of the Earth to depend on depth only, i.e. surfaces of equal conductivity are spheres concentric with the centre of the Earth. On a planetary scale, this is probably essentially true, but on a regional scale irregularities in the crust may be expected to influence the magnetic field, especially the shorter period transient field. This was pointed out by Chapman (Chapman & Bartels 1940, p. 712). Some evidence of these influences has been reported recently from central Europe (Wiese 1954), and from Japan (Rikitake & Yokoyama 1955; contains references to earlier work on the subject by the same authors).

Results from Australian magnetic observatories show characteristics that seem to be connected with eddy currents induced in a non-uniform conductor. The importance of this fact lies in the possibility that the irregularities in conductivity are located not in the crust (in the geological sense), but in the upper part of the mantle. In this case their distribution over the Earth may have considerable geophysical significance.

2. Observed directions of geomagnetic changes

Let us define the geomagnetic difference vector for an interval of time T as the vector difference between the geomagnetic field at one instant and that at an instant T later. If T is a fraction of an hour, the magnitude of the difference vector is usually only a few gammas (1γ equals 10^{-9} weber/m^2), but during disturbed conditions it can be some tens of gammas, and in extreme cases it exceeds 100γ.

At non-polar stations, the directions of the difference vectors for intervals of about 20 minutes are not distributed at random, but generally show a tendency to occur on or near a plane. This plane may be called the "preferred plane", and the great circle in which it meets the unit sphere may be called the "preferred circle". In this paper changes taking a few minutes to one hour are called "rapid fluctuations" to distinguish them from the components of the diurnal variation which have periods of at least three hours.

Rapid geomagnetic fluctuations can be analysed by scaling the total change in the three magnetic elements (ΔH, ΔD, ΔZ) over a number of equal intervals. H, D and Z indicate respectively, horizontal intensity, easterly declination and downward vertical intensity. The direction of the difference vector for a given interval is specified by the two angles θ and ϕ. θ is the angle made by the vector difference with the upward vertical, and ϕ is the angle made by its horizontal projection with magnetic north. Then

$$\tan\theta = (\Delta H + k\Delta D)/\Delta Z$$

and

$$\tan\phi = k\Delta D/\Delta H$$

where

$$k = H/3440$$

if H, ΔH and ΔZ are expressed in gammas and ΔD in minutes of arc, H being the average value of the horizontal intensity.

Directions can be conveniently shown by a polar diagram such as Figure 2a in which polar co-ordinates represent θ and ϕ. The radial scale for θ is chosen so that areas in the circle are proportional to the corresponding areas on unit

sphere. In the lower circle (for which $\frac{1}{2}\pi < \theta < \pi$), the radial distance from the centre represents $\pi - \theta$.

Table 1 shows the positions of magnetic observatories from which data are used in this paper. For the Australian stations the changes in each element over selected intervals were scaled from magnetograms. The intervals were selected without regard to time of day or season of the year. Only those intervals for which the magnitude of the difference vector exceeds 20γ were used. The initial epoch of each interval was chosen to coincide with a time mark on the magnetogram (i.e. at some multiple of 5 or 10 minutes after the hour), not necessarily at the beginning of a change in the magnetic field. For Darwin intervals always start on an hour or half-hour.

In general the intervals are not consecutive, although in some cases many were, e.g. for disturbed days at Macquarie Is. Very disturbed periods were avoided because a slight error in the time of beginning or end of the interval would cause a substantial error in the difference vector. Most intervals occur during bays on moderately quiet to moderately disturbed days.

Table 1

Positions of observatories and particulars of data

Observatory	Latitude	Longitude	interval mins.	data scaled from days	during	number of intervals	remarks
	° ′	° ′					
Darwin	12 26 S	130 50 E	30	17	July–Sept. 1957	98	
Alice Springs	23 47 S	133 51 E	20	9	June–July 1957	70	
Watheroo	30 19 S	115 53 E	20	12	Dec. 1951	71	
			60	22	Dec. 1951	58	
Gnangara	31 47 S	115 57 E	20	6	May–July 1957	47	
Toolangi	37 32 S	145 28 E	20	15	Apr.–Dec. 1955	131	
Macquarie Is.	54 30 S	158 57 E	20	4	Oct.–Nov. 1954	110	Dist.
			20	7	Nov.–Dec. 1954	60	Quiet
College	64 52 N	147 50 W					+
Sitka	57 04 N	135 20 W					+
Baldwin	38 47 N	95 10 W					+
Cheltenham	38 44 N	76 50 W					+
Tucson	32 15 N	110 50 W					+
Zi-ka-wei	31 12 N	121 20 E					+
Honolulu	21 18 N	158 06 W					+
San Juan	18 23 N	66 07 W					+
Amberley	43 10 S	172 44 E					+

+ indicates that values were not scaled; only qualitative information was obtained by inspecting published reproductions of magnetograms.

At Darwin northward and southward changes in the field are much more common than eastward or westward changes. To avoid crowding of points on Figure 2b many of the intervals containing principally northward and southward movements were deliberately ignored. Therefore the density of points in Figure 2b does not reflect the frequency of occurrence of directions of difference vectors at Darwin.

Australian Stations (Figure 1). Figures 2 and 3 show, on polar diagrams, the directions of the geomagnetic difference vectors scaled from magnetograms for the Australian stations. No account is taken of the magnitude of the difference vectors except that those less than 20γ have been omitted.

Macquarie Island differs from the other stations in being comparatively close to the auroral zone. On quiet days a downward change in the field is almost always associated with a southerly change, and an upward change with a northerly change. However there is no tendency for the directions to be confined to a plane.

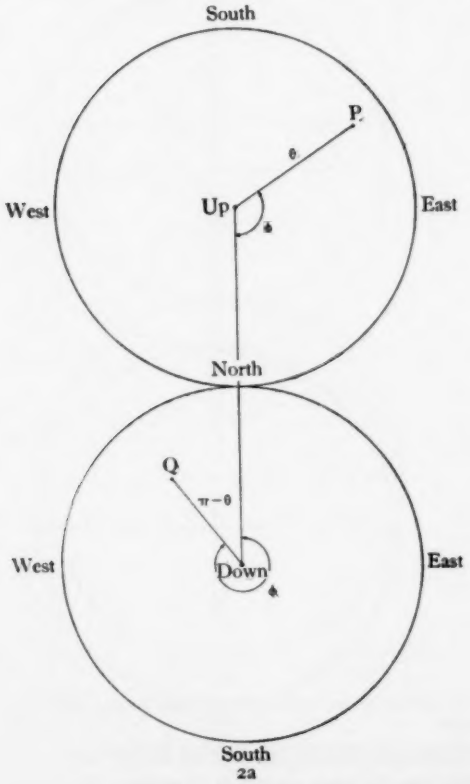
FIG. 1—Locations of Australian stations.

This would be expected if the transient field is due to an overhead current flowing eastwards or westwards in the auroral zone south of the station. However on disturbed days this tendency almost disappears (see Figure 3d). This is probably due to the fact that on these days appreciable current flows to the north of the normal auroral zone, often being to the north of Macquarie Island. At such times the

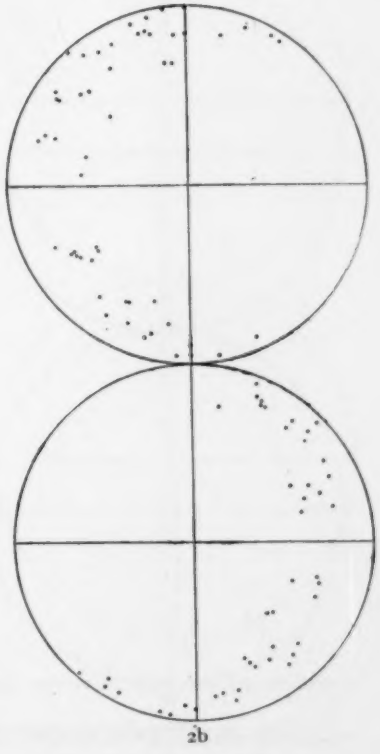
normal tendency is reversed and upward changes can coincide with southerly changes.

At each of the other stations there is a tendency for the difference vectors to lie in a plane. At Alice Springs (Figure 2c) the vectors are all almost horizontal. At Toolangi (Figure 3c) the vectors lie close to a plane which is almost horizontal, but is inclined slightly, the northern edge dipping downward.

At Darwin, Watheroo and Gnangara (Figures 2b, 2d and 3a) the plane containing the difference vectors is inclined quite steeply to the horizontal. At all



2a



2b

FIG. 2a—Explanation of polar diagrams. P represents a direction in the south-east-up octant, and Q a direction in the north-west-down octant.

FIG. 2b—Polar diagram showing directions of change vectors at Darwin.

three stations the plane dips downward to the east. This tendency is very strong at Watheroo. In fact only 13 per cent of the vectors lie more than 10° from the plane which has its normal at $\theta = 39°$, $\phi = 67°$. The pattern for Gnangara, which is only 110 miles from Watheroo, is almost identical with that for Watheroo.

All the polar diagrams of Figures 2 and 3 apply to 20 or 30 minute intervals. It is interesting to see how this pattern changes with the length of the interval. Watheroo data have been analysed for longer and shorter periods. For an interval of one hour the vectors tend to lie on the same plane as for 20 minute intervals, but they scatter much more. This is shown in Figure 3b.

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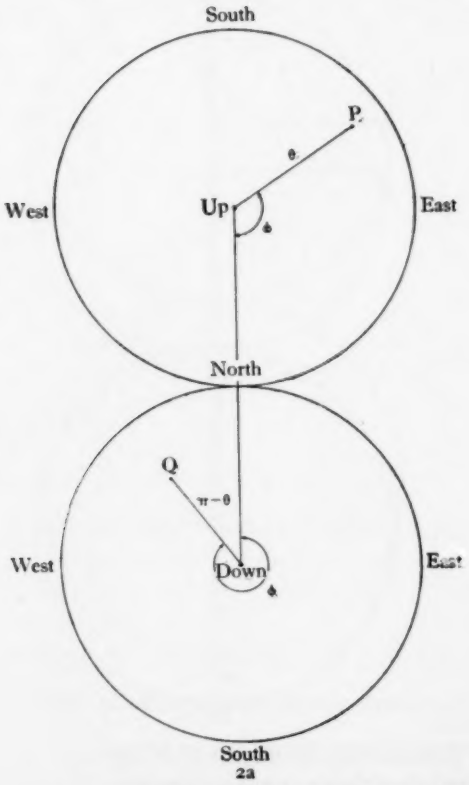
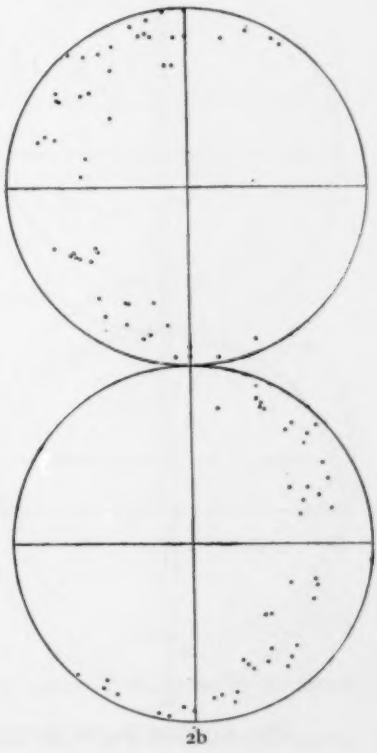


2a



2b

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It is not convenient to use the same method of analysis for shorter periods, but an idea of the behaviour can be obtained from an analysis of the more rapid variations recorded by a rapid run magnetograph, with a time scale of 18 cm per hour. These often take the form of more or less sinusoidal variations with periods between 1 and 4 min. It is found that variations in D and Z are in phase to within a quarter of a minute. The ratio of the amplitude of the Z wave to that of the D wave (considered as a variation in the magnetic east component) has an average

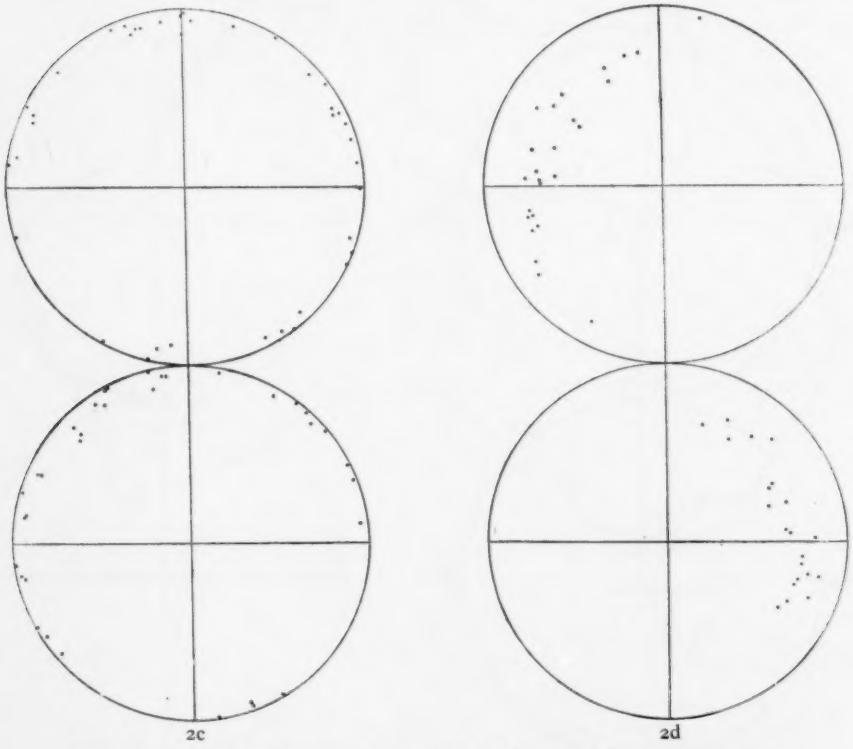


FIG. 2c—Polar diagram showing directions of change vectors at Alice Springs.

FIG. 2d—Polar diagram showing directions of change vectors at Gnangara.

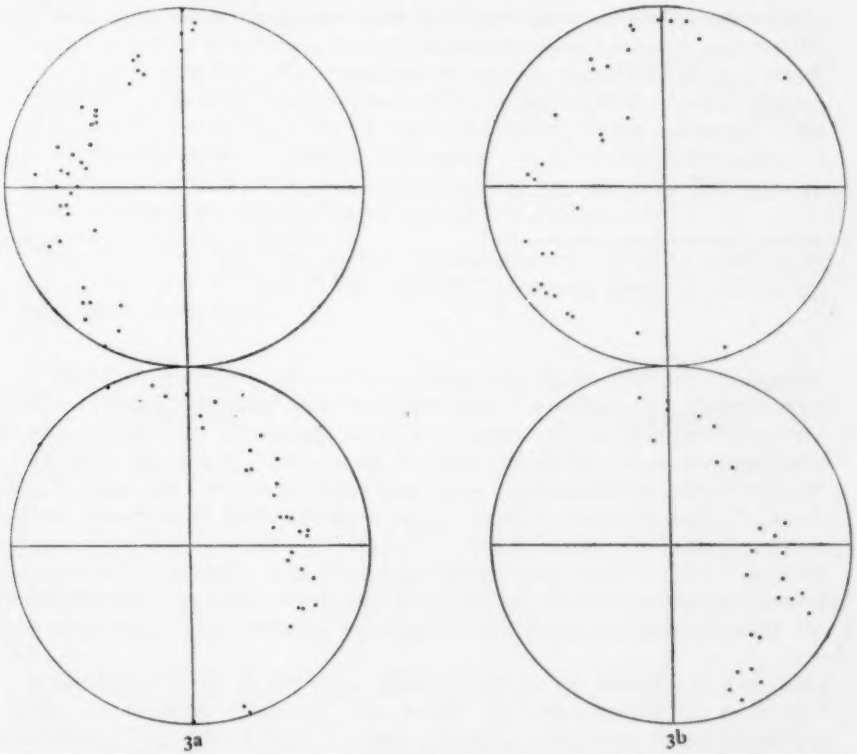
value 0·5, with a tendency to become smaller for the shorter periods. The corresponding ratio for 20 min periods is 0·8.

It appears, then, that much the same thing happens for more rapid fluctuations as for fluctuations of about 20 min period, except that the preferred plane tends towards the horizontal for shorter periods.

Non-Australian stations. If the difference vectors for short intervals are confined to the horizontal plane, this is shown in the magnetograms by the absence of rapid variations in Z. The behaviour at Watheroo or Darwin is characterized by a correlation between variations in D and Z. Since the preferred circle at Watheroo is inclined about an axis running NNW and SSE, and not N and S, the correlation is not perfect. In fact it can be reversed when the difference vectors are

directed almost north or south. This is the case for the few points in Figure 3a in the south–east–up and north–west–down octants.

In this way some qualitative idea of the behaviour of the difference vectors for a station can be obtained simply by looking at typical magnetograms. The following notes have been made from an inspection of reproductions of magnetograms published in the references mentioned:—



3a 3b

FIG. 3a—Polar diagram showing directions of change vectors at Watheroo for 20 minute intervals.

FIG. 3b—Polar diagram showing directions of change vectors at Watheroo for 60 minute intervals.

Amberley, New Zealand; (N.Z.D.S.I.R. 1940) there is a positive correlation between downward movement of Z and westward movement of D. The correlation is not perfect, and appears to be influenced by movements in H. The ratio $\Delta Z/\Delta Y$ is about 0·65 (cf. 0·8 at Watheroo). The pattern is generally similar to that at Watheroo, but the preferred plane is tilted in the opposite direction, and not quite as far from the horizontal.

San Juan, Puerto Rico (U.S. Department of Commerce 1953a); Short time changes in Z are small. There is a slight positive correlation between downward changes and westward changes, but the ratio $\Delta Z/\Delta Y$ is only about 0·18, i.e. the preferred circle is inclined at some 10° to the horizontal. The pattern is similar to that for Toolangi, but with the preferred circle tilted up towards the east.

Tucson, Arizona, U.S.A. (U.S. Department of Commerce 1955a). Rapid movements in Z do not occur at this station. The difference vector is confined very closely to the horizontal plane (except for comparatively long period variations such as diurnal variation). The pattern of difference vectors is similar to that for Alice Springs.

College, Alaska (U.S. Department of Commerce 1955b). The Z trace moves violently, sometimes being correlated with movements in D, sometimes with

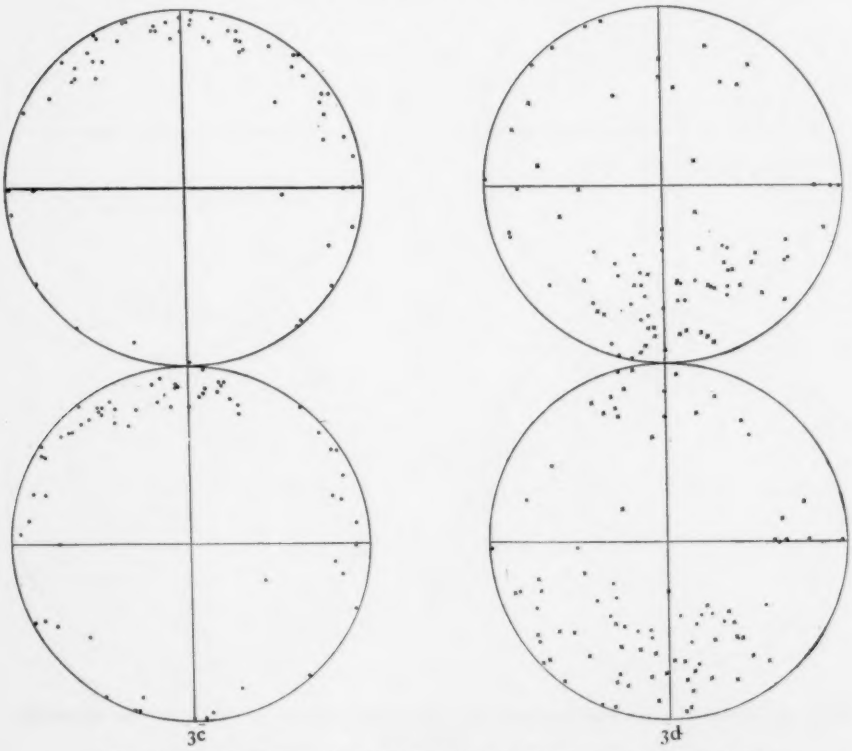


FIG. 3c—Polar diagram showing directions of change vectors at Toolangi.

FIG. 3d—Polar diagram showing directions of change vectors at Macquarie Island. Quiet days are indicated by dots, disturbed days by crosses.

those in H, but more often independently of both. This might be expected for a station so close to the Auroral Zone.

Sitka, Alaska (U.S. Department of Commerce 1954). This station is much the same as College. During the quieter periods there is a tendency for upward movements to correlate with southerly movements, which is the counterpart of the pattern for Macquarie Island.

Cheltenham, Maryland U.S.A. (U.S. Department of Commerce 1952). There is a tendency, although not a very strong one for difference vectors to lie on a plane inclined upward to the north west by about 10°.

Baldwin, Kansas, U.S.A. (Hazard 1909). At times a fairly good positive correlation between easterly and downward movement is shown, the ratio $\Delta Z/\Delta Y$ being about 0·5. However, often no correlation at all is evident. Rapid movements in Z occur although they are smaller than in the other elements. This station is clearly not the same type as are Alice Springs and Tucson.

Honolulu, Hawaii (U.S. Department of Commerce 1953b). There is a fairly definite positive correlation between downward and eastward movements, with $\Delta Z/\Delta Y$ about 0·7. This applies to movements occupying a major fraction of an hour. The situation is complicated by another correlation, which appears to apply only to very rapid movements such as sudden commencements. This is a positive correlation between northward and downward movements. A good example occurs just after 22 h (local time) on 1950 April 12. The apparent time constant of recovery in Z is only one or two minutes.

Zi-ka-wei, China (Zi-ka-wei 1905). Rapid movements in Z are small, being only about 1/10 of those in H. Upward movements generally accompany northward movements.

A good idea of the behaviour at European stations can be obtained from a paper by Wiese (1954), at least for a particular instance. Two maps are presented, each showing synoptically the changes in Z at a number of European observatories. There are two centres of Z-movement. In the northern one, which includes Rude Skov, Wingst, and Lerwick there is a positive correlation between downward and eastward movements. In the southern region, which includes Niemegk, Pruhonce and (possibly) Fuerstenfeldbruck, there is a positive correlation between upward and eastward movements. The line along which changes in Z are small lies close to Castellaccio, Chambon-la-forêt and Potsdam. In western Europe, downward movements accompany eastward movements, but become smaller towards the west.

A similar summary of Japanese stations is given by Rikitake & Yokoyama (1955). In Honshu, downward movements are accompanied by northward movements. The ratio $\Delta Z/\Delta H$ is about 0·6 in the south-east of the island, but decreases rapidly in a north–west direction, being almost zero along the north-west coast.

In both Japan and Europe the network of stations is sufficiently dense that some kind of regional distribution of the behaviour of the vertical component can be deduced. Maps of these regions showing this distribution give the impression that there exist anomalies within which rapid changes in Z are positively correlated with changes in some horizontal direction, and outside which rapid changes in Z are small. This would lead us to conclude that Watheroo, Darwin, Amberley, possibly Baldwin and Honolulu are on or near such anomalies. In view of the total number of observations considered here, it seems probable that such anomalies are quite common.

3. Deductions from Watheroo data

Both Wiese (1954) and the Japanese workers (Rikitake & Yokoyama 1955) attributed the intensity of vertical intensity fluctuations to the effects of eddy

currents beneath the Earth's surface. In fact they were able to separate the transient field into parts due to underground and overhead sources. This is impossible in the case of an isolated station. However it seems safe to attribute the behaviour at Australian stations to the same cause.

Let us concentrate on Watheroo, since this shows a closer correlation between the elements than do other stations. To explain the behaviour shown in Figure 3a by the form of the external field only, would require that the north or south flowing currents are confined to the east of Watheroo at all times of the day and seasons of the year. This is quite untenable. We must seek an explanation in the form of the internal field.

The behaviour can be summarized by saying that the total field cannot change rapidly in a direction north 67° east 51° up. This would result if the plane normal to this direction were the boundary of a semi-infinite body of considerable conductivity. This is clearly a physical impossibility, but the same effect may be caused by some physically possible configuration of conductivity underground. It would be interesting to know the time constant of the system of eddy currents causing the behaviour of the difference vectors at Watheroo. It is impossible to derive any precise information on this without knowing more about the primary field. However it is significant that the distribution of difference vectors for 60 minute intervals is not greatly different from that for 20 minute intervals. This suggests that the time constant of the eddy currents is at least of the order of one hour, and possibly greater. If, for instance, the primary field is nearly horizontal and the time constant of the eddy currents is considerably less than one hour, the points of Figure 3b should lie generally closer to the horizontal than those of Figure 2d.

It is hard to imagine any crustal feature with sufficient size and conductivity to support a system of eddy currents with a time constant as long as one hour. The only feature likely to have these properties is an ocean. It is important to try to decide whether, in fact, the oceans are the locations of the eddy currents controlling the directions of the difference vectors.

4. Effect of the oceans

The oceans can be considered as an irregularly shaped shell on the surface of the Earth, of infinitesimal thickness and of surface conductivity proportional to the depth. They have sufficient conductivity to influence greatly the direction of rapid fluctuations in the geomagnetic field. In fact Lahiri & Price (1939) showed that an ocean covering the whole Earth to a uniform depth of one kilometre would have an appreciable effect on the comparatively slowly varying diurnal variation field, although its effect on the still more slowly varying disturbance field is negligible.

It is very difficult to compute even a reasonable approximation to the effect of an actual ocean on the magnetic field at a nearby station. The difficulty is that almost any model sufficiently simple to yield numerical results must be greatly idealized. Probably the simplest model would be that consisting of a uniform ambient field and a flat semi-infinite ocean occupying half of the $Z = 0$ plane. It can be shown, however (Price 1950), that such a problem is indeterminate. Either the conductor or the imposed field must be considered to be of finite extent.

If the conductor is a finite horizontal lamina, a purely horizontal ambient field will not induce eddy currents, but only cause a separation of charge. When the dimensions of the conductor are sufficiently small that the ambient field can be considered uniform, some idea of the expected behaviour can be obtained from the treatment of Ashour (1950).

The Indian Ocean is about 3 000 km in radius and has an average depth of 4 km and a conductivity of 3 mho/m (Sverdrup, Johnson & Fleming 1942, p. 15 and 72). It would therefore have a time constant of 3 h if its depth were uniform. Considering irregularities in depth, and the fact that the primary field is not uniform over such an area, one hour is not an unreasonable value for the effective time constant.

When the dimensions of the ocean are large compared to the extent of the field, it may be considered as an infinite conducting sheet, and the method of Maxwell (1904, p. 294) may be applied. In this case, the behaviour depends on the form of the source of the primary field and its location. If the ocean is assumed to be 3 km deep, the eddy currents due to a sudden change in an overhead dipole at a height of 100 km decay to $1/e$ of their initial value after 5 minutes, those due to a line current at a height of 100 km in 23 minutes, and those due to a strip of uniform current density 1 000 km wide in 105 minutes. According to this theory, those from an infinite sheet of current should persist indefinitely. This is one aspect of the indeterminacy mentioned above.

Solutions in which the ambient field has a periodic structure have been studied by Price (1949), but the solutions depend critically on the length periodicity, and it is difficult to estimate this in the geomagnetic case.

It is not unlikely that the effect of a large ocean, at a point near its edge, will be to deflect the magnetic field upward if it is directed towards the ocean and downward if it is directed towards the land. This is the effect observed at Watheroo, in fact the direction of slope of the preferred plane is perpendicular to the coastline within a few degrees. Darwin has a smaller body of water to the west of it and has generally the same kind of behaviour (although the nearest deep water is the Banda Sea 300 miles to the north west). Alice Springs, far away from any ocean has almost no rapid change in Z. Toolangi has only small rapid changes in Z but it is reasonable to regard this as an inland station, for it is at least 250 miles from the nearest 100 fathom line. The effect of the comparatively shallow water over a continental shelf can be neglected compared to that of the deep ocean when considering intervals of the order of 20 minutes.

The behaviour of rapid fluctuations in other parts of the world, however, does not always agree with that to be expected if eddy currents in the oceans are the controlling influence. For instance the anomalous regions in Europe (Wiese 1954) have no apparent connections with coastlines or the edges of continental shelves. However it is interesting to note the situation at Coimbra in Figure 3 of that reference. The primary field is directed to the west, and a vertically upward induced field coincides with it. Coimbra is close to the western edge of the continental shelf.

The Japanese data are not quite what would be expected from eddy currents in the ocean (Rikitake & Yokoyama 1955 etc.) although it may be significant that the region where $\Delta Z/\Delta H$ is greatest is along the coastline which runs more nearly east–west than any other in the Japanese Islands.

Let us summarize the stations mentioned in Section 2; the direction in brackets below is that associated with an upward change in Z.

Strong Z movement	*Slight Z movement*	*No Z movement*	*Irregular*
Watheroo (W)	Toolangi (S)	Alice Springs	College
Gnangara (W)	San Juan (E)	Tucson	Sitka
Amberley (E)	Cheltenham (NW)		Macquarie Is.
Darwin (W)	Zi-ka-wei (N)		
Kakioka (S)			
Baldwin (W)			
Honolulu (W)			

Directions associated with the upward movements are roughly those to the nearest large ocean in the case of the first five of the first group and the first two of the second group. Both of the stations where Z is almost constant (over short time intervals) are well inland. However many features of this table cannot be so explained. For instance Darwin is several hundred miles from an ocean of appreciable depth and so should be influenced much less than Watheroo. The effect at Cheltenham is in the wrong direction, and the Pacific ocean is east of Zi-ka-wei (ignoring the continental shelf which extends to the Ryukyu Islands) not north of it. Baldwin is even further inland than Tucson. It is difficult to explain either of the effects observed at Honolulu by the presence of the ocean; in fact rapid changes in Z would not be expected to occur at all there, considering the extent of the surrounding ocean.

The question of whether the direction of rapid geomagnetic fluctuations are controlled by eddy currents flowing in the oceans, must be left unanswered for the moment. There seems to be little hope that calculations can be made sufficiently exact to settle the question. The best approach appears to be the setting up of temporary recording stations at well chosen locations, taking into account the edges of continental shelves rather than coast lines.

5. Non-oceanic causes of directional effects

The directional asymmetry of rapid geomagnetic fluctuations in many places requires the conductivity to be non-uniform in a horizontal plane below the surface of the Earth. If it can be shown that the oceans cannot explain the geographical distribution of these effects, we must look for a region of non-uniform conductivity in the upper part of the mantle. The Earth as a whole behaves as if there is a very rapid increase of conductivity to a value of at least 1 mho/m at a depth of the order of 600 km.

Two possibilities exist. Either there are conducting bodies above the 600 km level, or the boundary of the conducting "core" is not spherical, 600 km being an effective depth.

The simplest conducting body to consider is a sphere. In a uniform ambient field, this is equivalent to a dipole situated at the centre of the sphere and antiparallel to the ambient field.

The dipole equivalent to the Kakioka anomaly has been calculated (Rikitake, Yokoyama & Hishiyama 1953). It turns out to be at a depth of about 150 km. The authors have assumed that it is located beneath a point north of Kakioka, in which case the sense of the dipole is parallel to the ambient field. This corresponds to a sphere of negative conductivity, or less conductivity than the surrounding material. If the dipole is placed south of Kakioka, the corresponding sphere would have a conductivity greater than the surrounding medium.

It is interesting to see what the maximum effect of a buried sphere is. The ambient field can be considered to be uniform. This problem is dealt with in text books (e.g. Smythe 1950 p. 397). If the ambient field is horizontally northwards and the surface of the ground is tangent to the sphere, the resultant field is inclined upward south of the sphere and downward north of the sphere. The maximum inclination of the resultant field is 21°·5 at a distance equal to 0·62 R (R being the radius of the sphere).

The distribution of vertical intensity over a buried sphere would be something like that shown in Figure 2 of the paper by Wiese (1954). The centres of the inclination maxima are about 830 km apart, which indicates a depth of the equivalent dipole of 670 km. However this distribution apparently occurs with an eastward ambient field, so is probably not associated with an underground conducting sphere.

It is worth noting that the maximum inclination of the resultant field (21°·5) is considerably less than that observed at Watheroo (40°).

6. Conclusion

The vectors representing the change experienced by the geomagnetic field during short (about 20 minute) intervals have a strong tendency to lie on a plane at non-polar stations. At some places this plane is inclined to the horizontal by as much as 40°. This phenomenon is almost certainly due to some form of electromagnetic damping which inhibits rapid changes in the field in a certain direction (normal to the preferred plane).

The eddy currents causing this damping must flow either in the oceans or quite deep in the Earth, probably in the upper part of the mantle. If the latter is the case, a study of the directions of geomagnetic vectors could become a powerful method of exploring the upper part of the mantle, which in turn may throw some light on the large scale tectonic systems of the Earth. At present not enough is known of the regional distribution of the effect, nor of the theoretical interpretation. With modern geomagnetic recording instruments the collection of data should not be difficult. The theory, however, is complicated. It may be necessary to use model experiments to solve certain problems associated with irregularly shaped conductors.

Acknowledgments

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Evidence for an Intermediate Layer from Crustal Structure Studies in the Eastern Transvaal.

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(Received 1958 October 27)

Summary

Observations of the travel times of waves from Witwatersrand earth tremors along a route in the Eastern Transvaal are reported in this paper. It is considered that the most satisfactory interpretation is that the crust is two-layered. The velocities in the granitic layer are 6·0 and 3·6 km/s for P and S waves respectively. In the intermediate layer the P velocity lies between 6·7 and 7·2 km/s, and the S velocity between 3·95 and 4·15 km/s. The P_n velocity was found to be 7·96 km/s and the crustal thickness 36·6 km.

It was found that P_n arrivals at stations close to sea level were early with respect to the travel-time found for the plateau at a height of about 1 750 m.

1. Introduction

Investigation of crustal structure by studies of the travel-times of elastic waves from Witwatersrand earth tremors began in 1948. In the first field programme observations were made to the west of Johannesburg (Willmore, Hales & Gane 1952). The investigation was extended to the north, south and east of Johannesburg (Gane, Atkins, Sellschop & Seligman 1956). When this programme was complete it was clear that there were two aspects of crustal structure which merited further investigation. In the first place it seemed desirable that an attempt should be made to see whether there were any changes in travel-time associated with the changes in crustal thickness to be expected at an escarpment, and in the second that an investigation should be made of the limits which could be placed on the velocity distribution within the crust. The importance of the second question was stressed by Birch (1956).

It was known that the limiting factor on the accuracy of the previous travel-time studies had been the accuracy with which it was possible to locate the foci of the tremors. Investigations by Gane had shown that the inaccuracies in location arose as a result of differences in travel-time within the Witwatersrand system and that it was not possible to reduce them significantly by changes in the location procedure. The differences in travel time which could be expected to arise as a result of variation of crustal thickness are small and accordingly the field observation procedure was modified in such a way as to reduce the effect of errors of location. In earlier work the recording equipment at the field station was set in operation by a 1 000 c/s trigger signal sent by radio from the Bernard Price Institute (Gane, Logie & Stephen 1949). Attempts had been made to establish unattended field stations (Gane, Atkins, Sellschop & Seligman 1956, p. 294) but had not proved

completely satisfactory. It was clear, however, that satisfactory unattended satellite stations were necessary if the observation programme which was planned was to be carried out with the required accuracy in a reasonable time.

2. Equipment

Two solutions for the problems of unattended satellite stations were considered. The first possibility was to retransmit the 1 000 c/s triggering signal from the Institute by means of a V.H.F. transmitter (40 Mc/s) at the field camp and build transistorized receiving and triggering equipment for the satellite stations. The second possibility was to build transistorized receiving and triggering equipment for the satellites which would be operated directly by the signals from the Institute. It was decided that the first solution would be simpler as in this case there would be no need to provide for changing the frequency of the receivers at the unattended stations for day and night operation.

One of us (I.S.S.) designed and built a 30 watt 40 Mc/s transmitter to operate between the field camp and the satellites. The receivers at the satellite stations were super-regenerative with a 6C4 tube in the first stage. Thereafter transistors only were used. The trigger filter unit was a 1 000 c/s tuning fork filter of the same type as was used at the field camp. In general the 40 Mc/s transmitter relayed the signals from the Institute but when ionospheric conditions were bad it often happened that the trigger unit worked but the time signals were unreadable. Under such conditions the 40 Mc/s transmitter was modulated by a 1 000 c/s tone from a tuning fork at the field camp. This signal carried half-second time marks which were also recorded on the field camp record. With this arrangement it was possible to get relative times between the field camp and satellite stations even if a link with the Institute times was not possible.

The output from the seismometer was fed to a transistor preamplifier (Sacks 1957) buried with the seismometer and then to a transistor amplifier before being fed to the galvanometers. A filter unit which cut sharply between 2 and 5 c/s on the low-frequency side and between 30 and 35 c/s on the high-frequency side was incorporated in the amplifier. The low-frequency cut was introduced in order to reduce interference from microseisms of periods 1–2 s when operating near the sea. In the first field test it was found that the high-frequency cut was too sharp so that there was a tendency for random noise to produce ringing and also for the phases to lose character (Muir & F. W. Hales 1955). The high-frequency cut was modified and thereafter the amplifiers functioned satisfactorily.

The equipment proved to be very satisfactory. In the early stages some trouble was experienced with dry battery failure at the unattended stations and later the equipment was modified to work off a six volt accumulator.

The maximum distance between satellite and field camp was 68 km between stations 10 and 11.

3. Layout of stations

The route chosen for the investigation lay to the ESE of Johannesburg. The positions of the stations and the topography are shown in Figure 1 in which the contours are at, 200, 500, 1 000, 1 500 and 2 000 m. Up to station 10, *i.e.* for the first 240 km, the elevation varied between 1 650 and 1 850 m. Thereafter the elevation decreased fairly rapidly to the coastal flats region, the last 40 km of the route being at a mean elevation of about 100 m.

The observations were planned on the basis that for the first arrival phases the travel-time curve would be built up from measurements of the time difference in the arrival of a phase at two stations from the same tremor. In this way the effect of errors of location of the source would be avoided. In some cases it was convenient to operate with the satellites on either side of the base In these cases the base and one of the satellites were moved to new sites, the other satellite being left on its original site in order to provide a link between the two sets of observations. In other cases a base was set up with both satellites to the west of the base. After sufficient observations had been obtained both satellites were moved to the east of the base, which was not moved. This leapfrog technique proved very satisfactory.

The observations began in 1956 June, and were completed in 1958 January. During this time about ten months were spent on field observations.

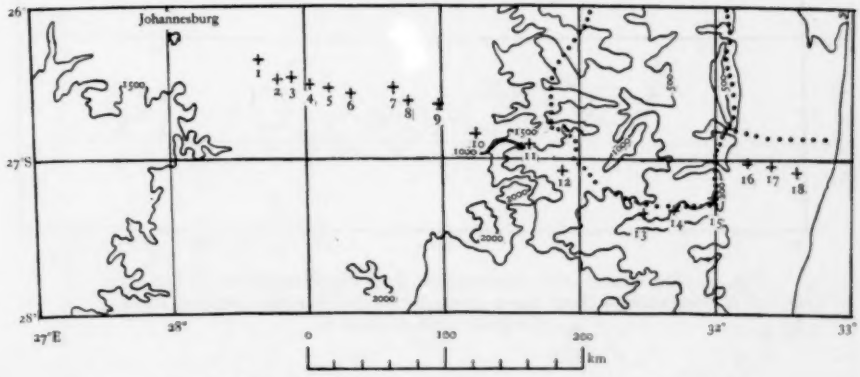

FIG. 1.—Positions of the stations. Contours at 200, 500, 1 000, 1 500 and 2 000 m

4. P_1 and P_n observations

In the case of the first arrival phases, P_1 and P_n, accurate values of the difference in travel-time between a pair of stations could be found by a comparison of the records of the same tremor at the two stations. In the case of P_1 these differences in travel-time formed the observational material for a least squares solution for the differences between the times of travel to station 2 and stations 1, 3, 4, 5 and 6. Station 7 was linked to station 6 directly. These differences in travel-time are given in Table 1 and are, of course, independent of any errors in location, or in the time link with the Institute records. Using the differences in travel-time from station 2, all P_1 arrivals were reduced to station 2. They were then adjusted to correspond to an origin roughly in the centre of the Reef, the adjustment being made on the basis of a velocity of 6 km/s. The distance from this origin to station 2 was 82·0 km and the mean time of travel $13{\cdot}66 \pm 0{\cdot}03$ s. The times and distances for the other stations, 1, 3, 4, 5, 6 and 7 were then calculated and are given in Table 1. Finally, a least squares solution gave the travel-time equation (4.1) for P_1.

$$t = (0{\cdot}00 \pm 0{\cdot}06) + (0{\cdot}1658 \pm 0{\cdot}0013)d \qquad (4.1)$$

$$\text{Velocity} = 6{\cdot}03 \text{ km/s}.$$

The P_1 observations are plotted in Figure 2, the small symbols representing individual observations and the large open circles the times obtained from the leap-frog technique as given in Table 1.

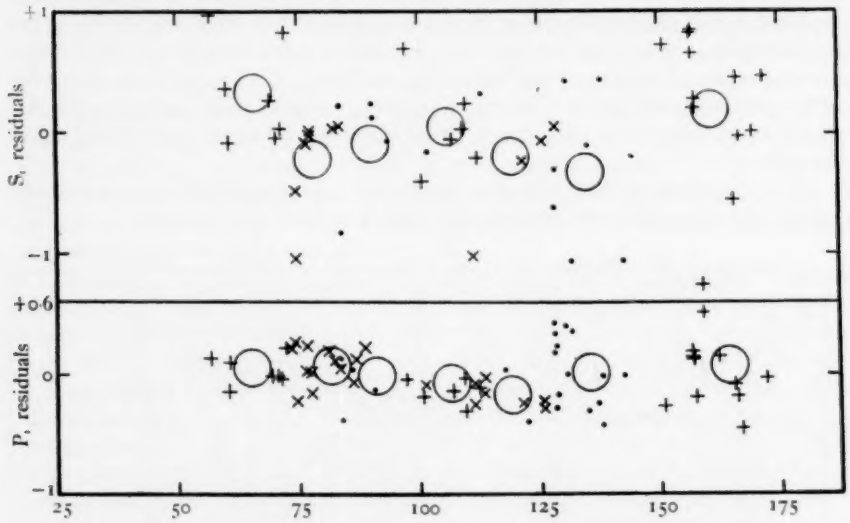

FIG. 2.—Deviations of P observations from the times given by (4.1) and of S observations from times given by (6.1). Abscissa: distance in km; Ordinate: residuals in s.

Table 1

Travel-times of P_1

Station	Travel-time from Station 2	Distance km	Time s
1	$-2{\cdot}76 \pm 0{\cdot}03$	65·48	10·90
2		82·00	13·66
3	$+1{\cdot}48 \pm 0{\cdot}06$	91·43	15·14
4	$+3{\cdot}74 \pm 0{\cdot}03$	105·40	17·40
5	$+5{\cdot}94 \pm 0{\cdot}07$	119·24	19·60
6	$+8{\cdot}87 \pm 0{\cdot}06$	135·84	22·53
7	$+13{\cdot}75 \pm 0{\cdot}07$	164·87	27·41

For P_n the observations consisted of the direct links which are given in Table 2. Using time differences from station 10, all P_n arrivals were reduced to station 10. They were then adjusted to correspond to the same origin as was used for the P_1 arrivals, the adjustment in this case being made using a velocity of 8 km/s. The

distance to station 10 from this origin was 231·30 km and the mean time of travel 35·95 ± 0·04 s. The times and distances for the other stations were then calculated and are given in Table 3. The P_n observations are plotted in Figure 3 in which again the small symbols represent individual observations and the large open circles the times obtained from Table 3.

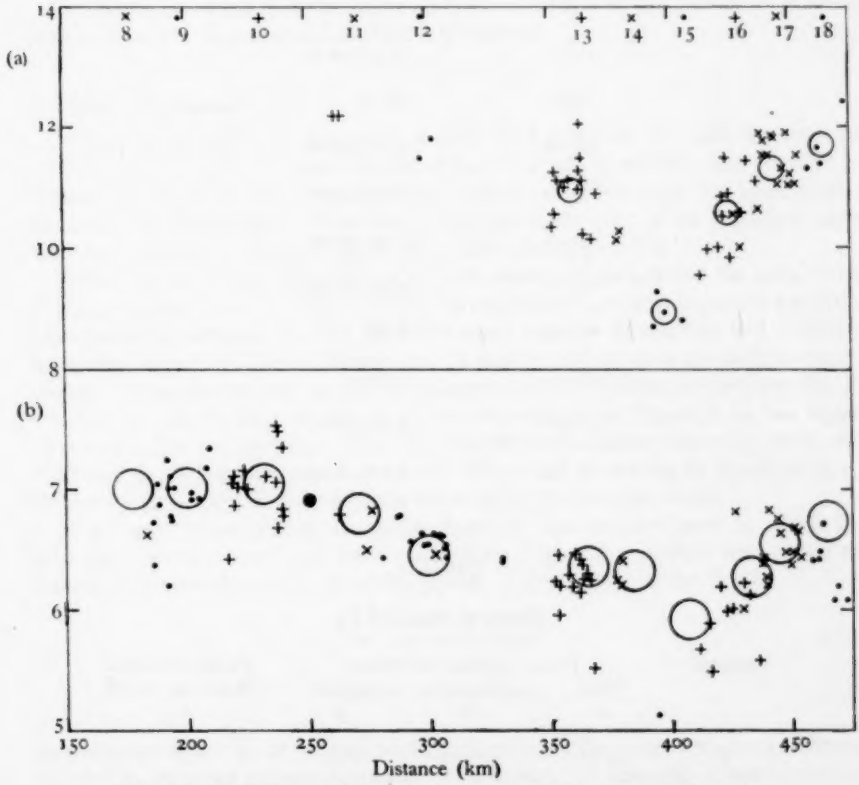

FIG. 3(a) Deviations of P_n travel-times from $d/8$ in s. The small symbols represent individual observations, the large open circles the times found by the leapfrog technique.
(b) Deviations of S_n travel-times from $d/4{\cdot}65$ in s. The small circles represent individual observations, the large circles the mean values of the deviations from $d/4{\cdot}65$ for each station.

Means of individual observations at stations confirm the travel-times found by the leapfrog technique as is shown by columns 4 and 5 of Table 3. The agreement between the leapfrog times and the means of the individual observations at stations 9 and 17 serves as an overall check on the leapfrog travel-times all along the line.

The escarpment begins immediately to the east of station 10 and consequently only three stations, 8, 9 and 10, can be used for the calculation of the travel-time equation for the plateau. From the times at these stations the travel-time equation (4.2) is found.

$$t = 6{\cdot}88 + (0{\cdot}1257)d \qquad (4.2)$$

$$\text{Velocity} = 7{\cdot}96\,\text{km/s}.$$

Table 2

Travel-times between stations, P_n

Stations	Time s
10–9	3·95 ± 0·02
10–8	6·74
11–10	4·71 ± 0·08
12–10	8·08 ± 0·02
13–12	7·95 ± 0·02
14–13	2·49 ± 0·05
15–13	4·84
16–13	7·83
17–16	2·42 ± 0·03
18–16	5·01 ± 0·03

Table 3

Times of travel of P_n

Stations	From leapfrog technique			From individual observns.
	Time s	Distance km	$t-d/8$ s	$t-d/8$ s
8	29·21	177·66	7·00	
9	32·00	199·95	7·01	6·89 ± 0·08
10	35·95	231·30	7·04	7·02 ± 0·08
11	40·66	270·89	6·80	6·60 ± 0·20
12	44·03	299·03	6·65	6·54 ± 0·03
13	51·98	364·94	6·36	6·22 ± 0·07
14	54·47	385·12	6·33	6·29 ± 0·10
15	56·82	407·14	5·93	
16	59·81	428·31	6·27	5·90 ± 0·10
17	62·33	445·40	6·55	6·49 ± 0·06
18	64·82	464·64	6·74	6·39 ± 0·11

Combining this equation with (4.1) it is found that P_n overtakes P_1 at 171·6 km. Confirmation of this estimate can be obtained from pairs of records in which P_1 was the first arrival at station 7 and P_n at station 9. Assuming velocities of 6 km/s for P_1 and 8 km/s for P_n four records give a mean crossover distance of $172{\cdot}9 \pm 1{\cdot}2$ km. Three pairs of records from stations 8 and 9 give similarly $174{\cdot}8 \pm 2{\cdot}4$ km.

It should be noted that the P_n velocity of 7·96 km/s in the Eastern Transvaal is lower than that found elsewhere in the Transvaal.

5. Other P phases

When the project was planned it was decided that very detailed observations would be made in the neighbourhood of 60 to 120 km to see if it was possible to determine accurately the point at which critical reflection from the Mohorovičić discontinuity first begins. However, reference to the plot of all P phases other than first arrivals in Figure 4 shows that this was not possible.

When attention was directed towards the observations beyond the cross-over, it was noted that the very definite second arrival phase invariably present on records from station 9 between 185 and 208 km was too early to be ascribed to P_1. There were also definite phases at stations 10, 11 and 12 which were too early to be P_1 phases. These phases are usually very large and show clearly on the records. A selection of records from stations 8 to 12 is reproduced in Figure 5. In this figure P_2 is marked by a broken line. The part with the arrow shows where the phase was read and the other part where it should have been according to equation (5.1). Where the line is not broken the two times differ by less than 0·04 s.

We regard these phases as coming from an intermediate layer in which the velocity is about 7 km/s and have marked on Figure 4 a dashed line which we regard as the travel-time curve of this phase. The equation of the line is:

$$t = 4{\cdot}91 + 0{\cdot}1390\,d \qquad (5.1)$$

$$\text{Velocity} = 7{\cdot}19 \text{ km/s}.$$

In cases like this it is, of course, possible to choose other lines by giving different weights to different groups of points. In this case, for example, it can be argued that as the P_n phases were early at station 12, it is likely that the intermediate phases would also be early and should not be taken into account in determining the travel-time equation. If this is done then the velocity for the intermediate layer will be less than that given in (5.1).

There is some evidence that the apparent velocity of the phase increases with distance. At station 9 the second phase is always clear and it is possible to determine fairly accurately the difference in travel-time between it and P_n. These differences in travel-time are plotted in Figure 6. A least squares solution leads to the travel-time equation

$$t = 3{\cdot}03 + 0{\cdot}1490\,d \qquad (5.2)$$

$$\text{Velocity} = 6{\cdot}71 \text{ km/s}.$$

It should be noted that the effects of errors of location are minimized in Figure 6 as compared with Figure 4.

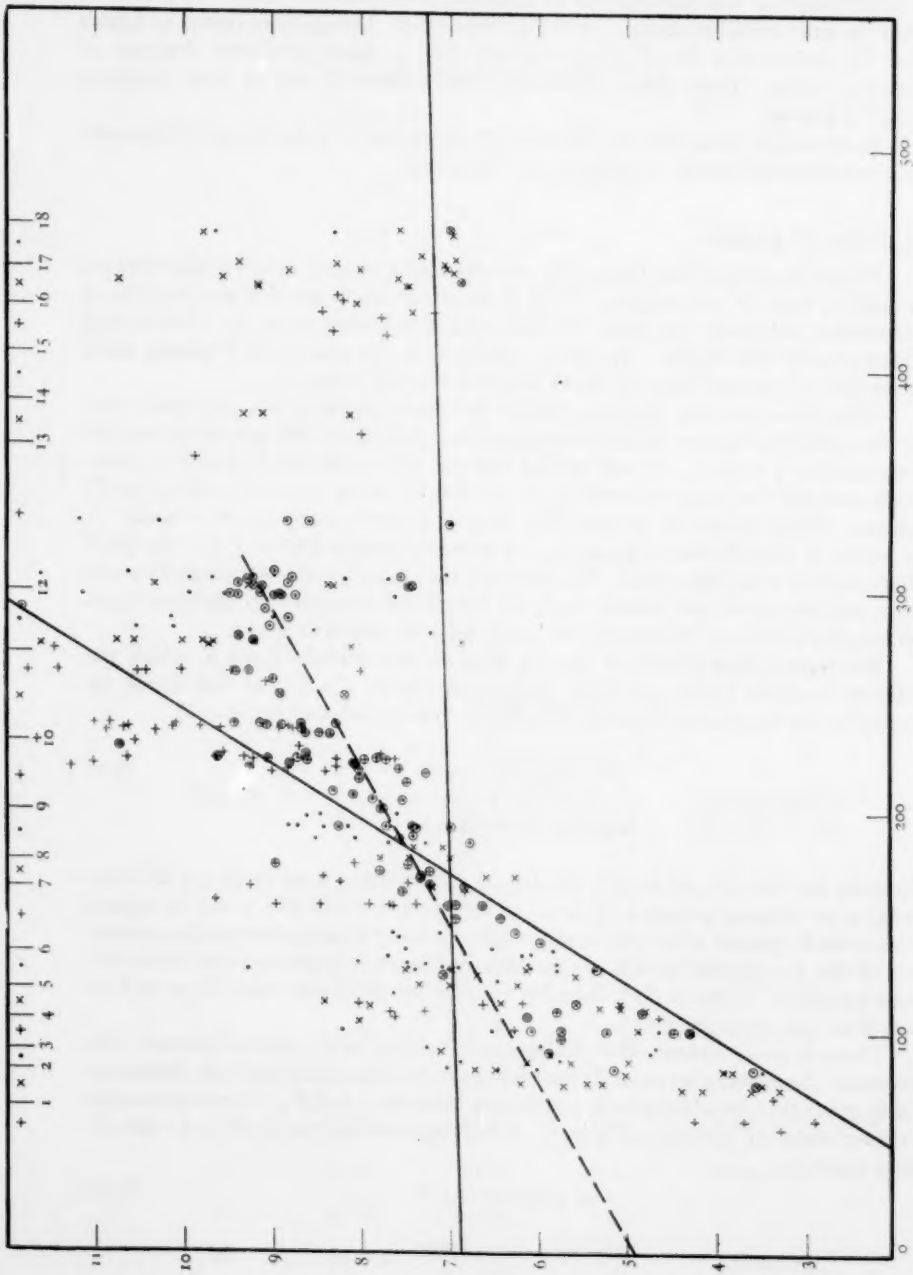

FIG. 4.—*P* phases other than first arrivals. Where the symbol is enclosed in a circle the phase was regarded as definite. Ordinate: $t - d/8$ in s.

The question of whether, or not, there is an intermediate layer has been much discussed in recent years. The difficulty arises because, as Bullard (1954) has remarked, the intermediate layer P phase is never a first arrival in many series of observations. In the case of the present observations it is certain that there is no phase which is more than $\frac{1}{2}$s earlier than the P_1 or P_n arrivals at the cross-over and we are of the opinion that the first arrivals are always either P_1 or P_n. Bullard (1954) has emphasized the difficulty of establishing the existence of new phases.

"Such readings are difficult to interpret, for it frequently happens that individual records give clear phases that cannot be correlated with anything on the records of neighbouring stations. When there are several such readings it becomes to some extent a matter of choice whether they shall be joined by a line of the time-distance plot, and whether features on other records shall be read because they are near the proposed line. It is only too possible for an observer who is determined to get all the information that can be extracted from the records to be imperceptibly led to accept points that lie near the line and to reject ones that do not and to finish with apparently convincing evidence for the existence of a phase that is entirely spurious." The difficulty of identifying second arrival phases is made more acute by the fact that conversion of phases occurs at irregularities in the surface as was shown by Tuve and Tatel (1955).

Nevertheless the authors are reasonably confident that the observations reported here are not spurious and do not refer to P_1. The calculated time of arrival of P_1 has been marked on the records reproduced in Figure 5. It is clear that the general characteristic of the records is that the new energy arrives in advance of the P_1 time by an amount which increases with the distance. Qualitatively, therefore, the records lend support to the view that there is an increase in velocity in the crust at depth.

It is also clear that the character of the records is not determined entirely by the station. This is shown most clearly by comparison of the records B and C of Figure 5. These records are from approximately the same distance, but from stations 8 and 10 which were 56 km apart. Other records from station 10 look entirely different. (Compare records K and L). Another point of some importance is the close similarity of the Eastern Transvaal records to those obtained in the Western Transvaal, as is shown by a comparison of H and J of Figure 5. Record H is a reproduction of a Western Transvaal record. (For other records from this distance range see Figure 6 of Willmore, Hales & Gane 1952).

Finally, attention should be drawn to records A and C of Figure 5. These records both come from station 8, A being obtained 2 km before the cross-over and C 11 km beyond the cross-over. In A the first arrival is P_1 whereas in C it is P_n. The close similarity of these records was noted at an early stage of the work. It was difficult to believe that the large second arrivals on the records could be P_n for A, and P_1 for C. It is thought now that the large second arrivals following closely on the start in these records are in fact the P_2 phase.

The large amplitudes associated with the P_2 phase from 170 to 250 km or more are noteworthy. The simplest explanation would appear to be that the velocity increases with depth in the intermediate layer. This point requires further investigation in a region where there are no complications from possible escarpment effects.

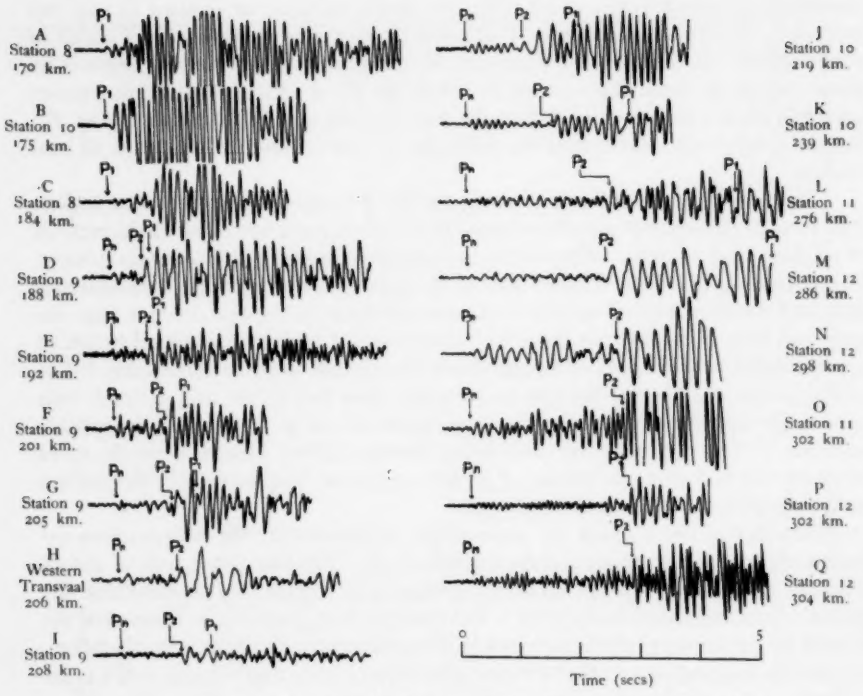

FIG. 5.—Records showing the P_2 phase. N.B. The phases marked P_1 in records B and C are P_n.

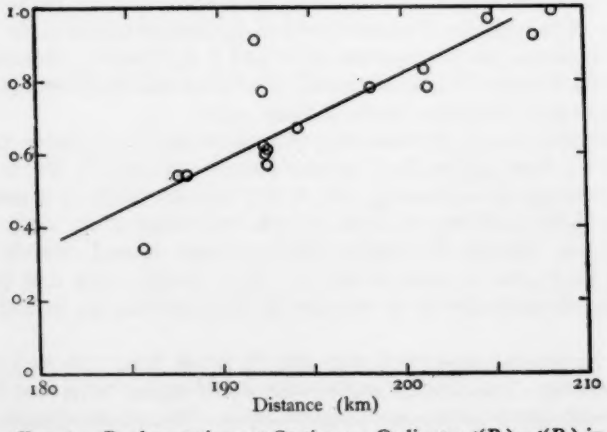

FIG. 6.—P_2 observations at Station 9. Ordinate: $t(P_2) - t(P_n)$ in s.

6. S phases

In the case of the S phases the reading error is comparable with the error in location. The greater reading error arises in part at least from the fact that a new second arrival may be in or out of phase with the existing wave pattern. In the latter case it is likely that the phase will be read later. The S_1 observations are plotted in Figure 2. The observations for stations 1 to 7 were used to calculate an S_1 travel-time equation by least squares, the solution being:

$$t = (0{\cdot}32 \pm 0{\cdot}26) + (0{\cdot}2764 \pm 0{\cdot}002)d \qquad (6.1)$$

$$\text{Velocity} = 3{\cdot}62\,\text{km/s}.$$

The S_n observations are plotted in Figure 3. The small symbols represent individual observations and the large circles show the mean distances and mean values of $t - d/4{\cdot}65$ for the tremors observed at each station. The velocity of 4·65 km/s was chosen arbitrarily.

It is clear that at stations 10, 11 and 12 between 200 and 330 km there are only a few isolated observations which can be ascribed to S_n. From stations 13 outwards, however, the phase was well observed. At station 9 there are a number of clear phases but the arrival-times of the three possible phases S_1, S_2 and S_n lie so close together that it is not possible to identify these with any one of the phases.

It is noteworthy that the observations show the same pattern as those for P_n with a very early arrival at station 15. It is not surprising that S_n was in general not observable at stations 10, 11 and 12, for at these stations P_n was always small and satisfactory observations were only obtained from large tremors under low noise conditions. For S_n the background is determined by the tremor itself and there is no improvement in signal to noise ratio with size of tremor. When it was realized that there were no S_n readings in this distance range, the records were re-examined to see whether the phase could be identified when it was known where it should be. This was sometimes possible, but it was evident that these phases would not have been read in the ordinary way and they have not been shown on the plots.

As there are no satisfactory observations of S_n on the plateau it is not possible to calculate a travel-time for S_n under plateau conditions. The average velocity of S_n from station 13 to 17 is 4·56 km/s. This velocity is lower than that found for S_n in the western, northern and southern traverses.

Although S_n phases were not recorded at stations 10, 11 and 12 there were well defined S phases on the records at times which were too early for S_1. These phases are large and definite as is shown by the selection of records reproduced in Figure 8. On each record the estimated times of arrival of S_n and S_1 have been marked. For S_2 the part of the broken line with the arrow marks the S_2 phase as read, the other part of the line indicating the time of arrival as found from equation (6.2).

All S readings other than those used for the S_1 travel-time equation and the possible S_n readings from station 13 to station 18, have been plotted in Figure 7. Also marked on this figure is a line giving the travel-time for this phase as determined by inspection. The equation of this line is

$$t = 5{\cdot}83 + 0{\cdot}2477\,d \qquad (6.2)$$

$$\text{Velocity} = 4{\cdot}04\,\text{km/s}.$$

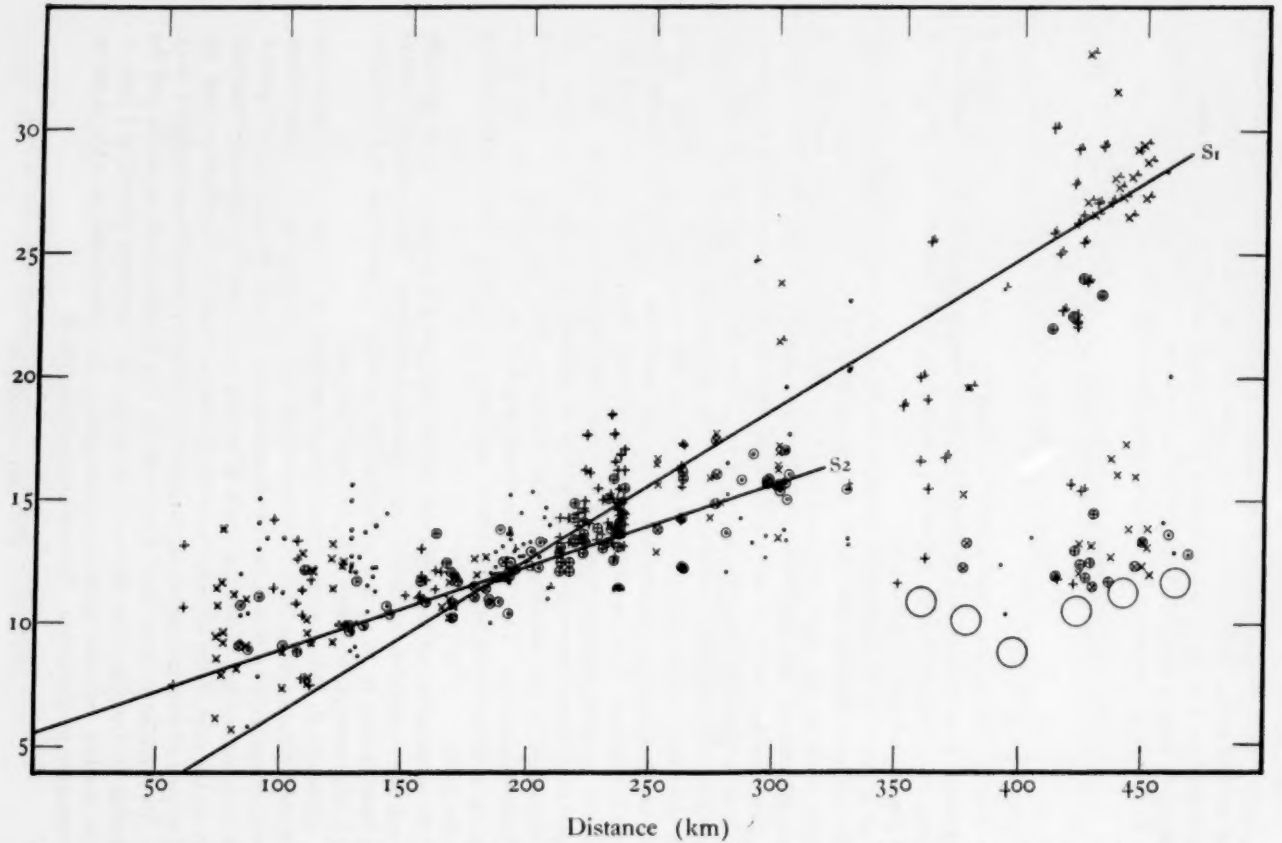

FIG. 7.—*S* phases other than S_1. Where the symbol is enclosed in a circle the phase was regarded as definite. Large circles show mean S_n readings at stations 13–18. Ordinate: $t-d/4{\cdot}65$ in s.

An attempt has been made to estimate the limits within which the S_2 velocity lies by drawing other lines through the points. It is thought improbable that the velocity lies outside the range 3·95 to 4·15 km/s. We regard the existence of this phase as being reasonably well established and associate it with the intermediate layer P phase designated P_2 in this paper.

It will be noted on Figure 7 that there are a number of observations with the letter L alongside them. These refer to waves with periods of $\frac{1}{3}$ to $\frac{1}{2}$ second which are found occasionally at short distances but were found almost invariably on the records for station 17. The velocity of the phase is approximately 3·6 km/s. It is possible that this group of phases represents early observations of the L_g phase.

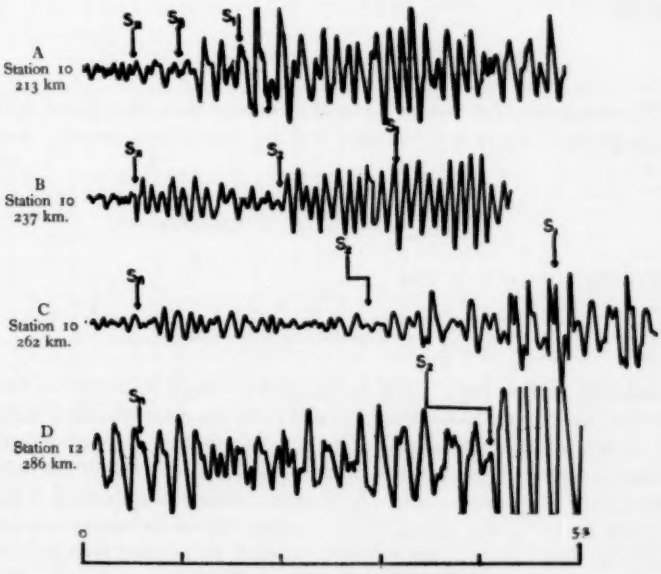

FIG. 8.—Records showing the S_2 phase.

7. Crustal structure

The principal uncertainty in crustal structure arises from the difficulty in determining the travel-time equations for the intermediate layer phases. Two equations (5.1) with a velocity of 7·19 km/s, and (5.2) with a velocity of 6·71 km/s were given for P_2. Using these equations with (4.1) and (4.2) we find from the P phases the crustal thicknesses given in Table 4. In deriving these values it has been assumed that the mean depth of focus of the tremors was 2 km. As there were no S_n observations on the plateau it is not possible to determine the depth to the Mohorovičić discontinuity from the S data. Equations (6.1) and (6.2) give a thickness for the granite of 24·8 km.

Qualitatively the observations beyond station 10 are in accord with the hypothesis that the crust is thinning towards sea level, but the greatest decrease in intercept time occurs between stations 10 and 13 which is earlier than would have been expected from the topography.

Table 4

Crustal structure in the Eastern Transvaal

	From Eqn. (5.1)		From Eqn. (5.2)			
	P vel. km/s	Thickness km	*P* vel. km/s	Thickness km	*S* vel. km/s	Thickness km
Layer 1	6·03	28·2	6·03	21·9	3·62	24·8
Layer 2	7·19	8·4	6·71	14·7	4·04	
Depth to Morohovičić discontinuity		36·6		36·6		
Layer 3	7·96		7·96			

The P_n travel-time for station 13 is 0·7 s earlier than that given by equation (4.2) for the plateau, where it is assumed that the structure is normal. Accordingly we find

$$-0{\cdot}7 = 0{\cdot}1080\Delta H_1 + 0{\cdot}0593\Delta H_2 \tag{7.1}$$

for a P_2 velocity of 7·19 km/s, and

$$-0{\cdot}7 = 0{\cdot}1080\Delta H_1 + 0{\cdot}0800\Delta H_2 \tag{7.2}$$

for a P_2 velocity of 6·71 km/s. ΔH_1 is the difference in thickness of the granite layer between the plateau and station 13, and ΔH_2 the corresponding difference in thickness of the intermediate layer. Further information is needed before ΔH_1 and ΔH_2 can be found. However, it is worthwhile to remark that if the only change as compared with the plateau is in H_1 then the change required is 6·5 km from both (7.1) and (7.2). If the change is in H_2 then the estimates are 11·9 km from (7.1) and 8.8 km from (7.2). For (7.1) it is possible to account for the observation by replacing 14·4 km of granite by the same thickness of intermediate layer material but this is not possible for (7.2).

It is possible that a study of the gravity observations along the route will resolve some of the ambiguity arising from the two-layer structure.

8. Discussion

Byerly (1956) reviewed all the available seismological evidence on subcontinental structure and came to the conclusion that the P^* layer is a separate "entity which makes it deserve the title of layer rather than being just thought of as just a gradual change from the material above it". Byerly's review of the travel-time studies (refraction studies) shows that the velocities ascribed to the intermediate layer and the thicknesses given for the intermediate layer vary very widely. The structure inferred for the Eastern Transvaal is in fairly good agreement with that determined by Reich, Schulze & Förtsch (1948) and Rothé, Peterschmitt & Stahl (1948) in studies based on the Haslach explosions in the Black Forest region.

Work done since 1956 tends to support the view that there is an intermediate layer. Press (1958) presented evidence in support of the view that a layer with

velocity 7·2 to 7·4 km/s occurs at a depth of 20 km beneath California and Nevada. A similar conclusion is reached by Richards (1958) on the strength of explosion studies in Western Canada.

It is natural to enquire whether there is any method other than the study of travel-times by which it is possible to decide between a single-layer and a two-layer crust. One possibility is the study of reflections at small angles of incidence, *i.e.* by the application of ordinary reflection prospecting techniques to crustal structure. Junger (1951) identified a reflection from a discontinuity surface at a depth of 18 to 21 km on records made with only 25 pounds of explosive in Montana, United States of America. He suggested that these reflections came from the base of the granite layer. Reich (1953) identified reflections from discontinuities at depths of 20·3 and 27·6 km on the records of blasts of 3 000 kg of explosive in Northern Germany.

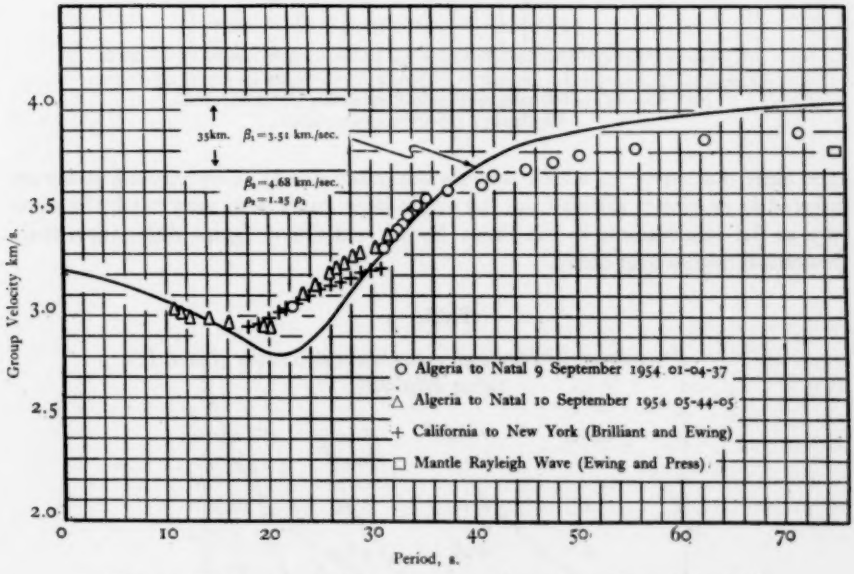

FIG. 9.—Observed and theoretical dispersion of continental Rayleigh waves (Press, Ewing & Oliver 1956).

The reflection procedure has much greater resolving power than the refraction procedure, and it is clear that a closely observed profile of reflection observations would resolve many of the uncertainties about the behaviour of the boundaries between the layers in the escarpment region.

Another possibility lies in the study of the velocity/period relationship for Rayleigh or Love waves. For Africa, Press, Ewing & Oliver (1956) have published a curve showing the relation between period and velocity for the Rayleigh waves from an Algerian earthquake observed at Pietermaritzburg. This figure is reproduced as Figure 9. The authors remark that the discrepancy between the observed points and the theoretical single-layer curve shown in the diagram is to be interpreted as an effect introduced by an increase of velocity with depth within the

crust. This conclusion is supported by comparison with Figure 10 which shows the theoretical curves calculated for single- and two-layer crusts by Haskell (1953). The parameters for which Haskell's curves were calculated are given in Table 5.

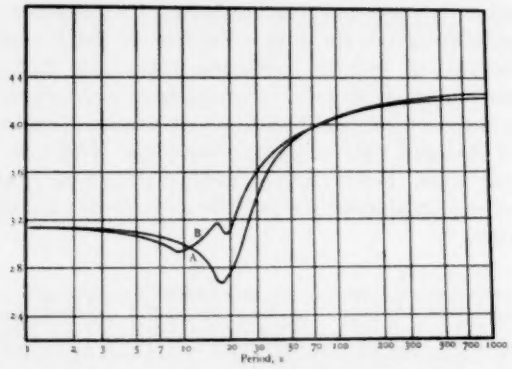

FIG. 10.—Theoretical group velocity curves (after Haskell).
Ordinate: group velocity, km/s.

It is clear that curve B, which corresponds most closely to the crustal structure inferred in Section 7, differs from the single-layer curve A in very much the same way as the observations in the Press, Ewing and Oliver figure differ from their theoretical single-layer curve.

Table 5

Parameters of Rayleigh group velocity curves A and B (after Haskell)

	Layer	*P* vel. km/s	*S* vel. km/s	Thickness km
A	1	6·14	3·39	28·38
	2	8·26	4·65	
B	1	6·14	3·39	13·60
	2	7·00	4·04	21·21
	3	8·26	4·65	

This point is of considerable importance for the surface wave data depend on the average conditions over the whole path from Algeria to Natal, a distance of more than 3 500 miles.

9. Uncertainty in crustal structure

In Sections 5 and 6 it has been pointed out that the observations in the Eastern Transvaal are best interpreted in terms of the existence of an intermediate layer. However, it is clear that it is often difficult to establish whether or not there is an

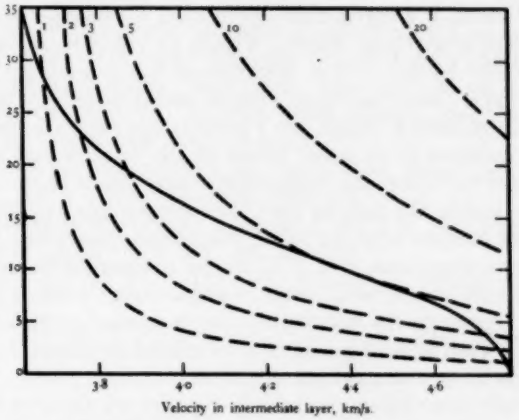

FIG. 11. Plot showing effect of interpreting travel-times from a two-layer crust in terms of single-layer theory. *P* waves. Ordinate: thickness of intermediate layer, km.

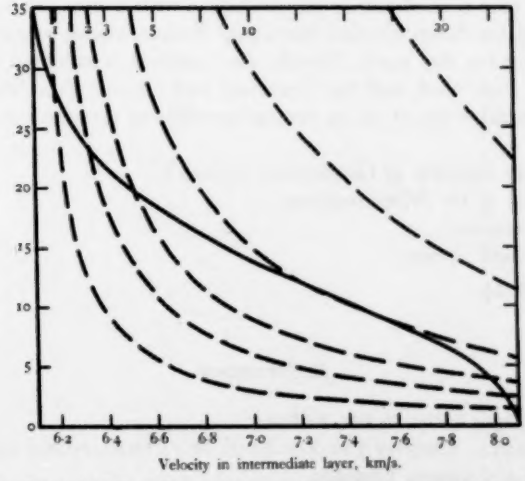

FIG. 12.—Plot showing effect of interpreting travel-times from a two-layer crust in terms of single-layer theory. *S* waves. Ordinate: Thickness of intermediate layer, km.

intermediate layer in any particular area, and it is therefore of interest to examine what error will result if a travel-time curve from a two-layer structure is interpreted in terms of single-layer theory. Figure 11 refers to *P* waves and is constructed for a crust having a fixed thickness of 35 km made up of $(35\text{-}x)$ km of material of velocity 6·1 km/s overlying x km of intermediate layer which again overlies material with velocity 8·1 km/s. In Figure 11 the region to the left and below the full curve corresponds to those values of the velocity and thickness of the intermediate layer for which the intermediate layer phase is never a first arrival, while that above and to the right of the curve corresponds to velocities and thicknesses of the intermediate layer for which the intermediate phase is a first arrival. The dashed curves numbered, 1, 2, 3, 5, 10 and 20 indicate the errors which arise in interpreting a two-layer crust in terms of single-layer theory. The curve marked 5, for instance, represents the velocity and thicknesses of a two-layer crust which would result in a 5 km underestimate of total crustal thickness if the travel-times are interpreted as from a single-layer structure.

Clearly the only cases which can arise in practice are those in which the intermediate layer phase is never a first arrival and it follows that for the postulated parameters the maximum error possible is 5 km.

Figure 12 gives similar information for the *S* phases, the velocity in the uppermost layer being 3·625 km/s and below the crust 4·78 km/s.

10. Acknowledgments

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1958 *October* 24.

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Remanent Magnetism in Jurassic Red Limestones and Radiolarites from the Alps

Robert B. Hargraves and Alfred G. Fischer

(Received 1958 December 12)

Summary

Red Jurassic limestones and radiolarites from the Kammerköhr range on the Austrian–German frontier show rather consistent remanent magnetic vectors. The average North Pole position for lower Jurassic rocks (red limestones) is latitude 53° N, longitude 112° E and for Middle Jurassic rocks (red radiolarites) latitude 58°·5 N, longitude 128° E.

1. Introduction

In the Northern Calcareous Alps the major portion of the Jurassic system is represented by a rather thin section (of the order of 100–200 m) of fine-grained marine rocks, varying from grey and red limestones (the Kieselknollenkalk, red cephalopod limestone, red Knollenkalk, Adneth beds, etc.) to maroon or greenish grey radiolarites—impure, calcareous cherty rocks replete with the remains of radiolarian tests.

In 1957 Fischer measured a detailed section of this sequence, and collected oriented samples for magnetic analysis. This was carried out by Hargraves, with a "spinner"-type magnetometer, kindly made available by the Geophysical Laboratory of the United States Geological Survey, through the courtesy of Dr James R. Balsley.

For financial support we are indebted to the Socony Mobil Oil Company, Inc., and its affiliate, the Magnolia Petroleum Company, and to funds of the Eugene Higgins Trust allocated to Princeton University; for stimulation and encouragement to Professors A. F. Buddington and Franklyn B. Van Houten.

2. Location

The profile sampled is exposed on the west face of the Scheibelberg in the Kammerköhr range. It lies essentially on the German–Austrian frontier, and very near the boundary between the Austrian provinces of Salzburg and Tirol. The co-ordinates are 47° 37′·5 N, 12° 34′·5 E.

The structure of the area is rather simple. The rocks sampled are flat-lying, from the axis of an open syncline which plunges gently eastward, to vanish at Lofer, some 10 km to the east, under the Berchtesgaden thrust sheet. There is some question as to whether this syncline and the adjacent rocks are essentially in place, or transported as part of a thrust sheet. Various thrusts have been mapped farther north, along the Alpine margin, and by analogy with the western Alps various geologists have believed these to be essentially flat. The adherents of this view assume that one or more of these thrusts are present at a depth below the

Kammerköhr range, and that the range is part of a "Staufen-Höllengebirge thrust sheet" (Schaffer 1951). Others have suggested that the frontal thrusts of the eastern Alps are high-angle structures, and that the rocks behind them are essentially autochthonous. In any case, few would care to defend the ultranappist view that these rocks originated on the southern margin of the Alpine trough. If they were thrust, movement was probably of the order of kilometres or tens of kilometres. It has therefore not moved the rocks over a sufficient distance to invalidate their palaeomagnetic applications; neither can one visualize tectonic rotation sufficiently great to have disoriented the magnetic vectors.

3. Stratigraphy and sedimentation

The general stratigraphy of the northern Alps is described in many standard works, among them Schaffer (1951). That of the Kammerköhr range was described by Hahn (1910). Here the Lower Jurassic is represented by limestones—red limestones of various types which interfinger northwestward with the grey to white, cherty Kieselknollenkalk. Most of the standard Liassic ammonite zones have been recognized within this sequence. These limestones are generally conformably overlain by radiolarites—bedded, impure, calcareous, radiolarian cherts, mainly of maroon colour, which in turn grade upward, and in their upper part interfinger with the siliceous Oberalm limestones of latest Jurassic (Tithonian) age. Diagnostic fossils are lacking in the radiolarite, but its stratigraphic relations suggest that the 20 m or so of radiolarite represent essentially all of the Middle and most of the Upper Jurassic.

The profile measured by Fischer on the Scheibelberg is shown in Figure 1. Here the Kieselknollenkalk represents the lower and middle portions of the Lower Jurassic. Hahn (1910) reports *Aegoceras*, an indication that the unit extends into the lower Pliensbachian.

The overlying red limestones and mudstones carry *Amaltheus* (Hahn 1910) and *Harpoceras*, and represent the upper part of the Lias—specifically, the middle and upper Pliensbachian and the lower Toarcian. The slumped zone and succeeding break at the top of this section suggest that the upper Toarcian is not represented.

The radiolarite here is about 20 m thick, but only the lower 15 m are shown in Figure 1. The basal portion is green to grey. The upper contact with the Oberalm beds is covered.

The Kieselknollenkalk and the basal, grey portion of the radiolarite are not sufficiently magnetized to permit determinations of remanent magnetism. The samples here reported on—shown at the left side of Figure 1—are in two distinct groups: One from the red limestones (late Lower Jurassic), and one from the maroon radiolarite. It appears probable that samples 170 up to 369 are Middle Jurassic; sample 381 might be Upper Jurassic, but in the absence of recognizable guide fossils the Middle–Upper Jurassic boundary within the radiolarite remains undefined. The radiolarite samples were therefore treated as one unit.

The Jurassic sediments are quite unlike those found in normal epicontinental deposits. Their fine grain, pelagic faunas, and highly oxidized state are more suggestive of modern deep-sea deposits, and suggest deposition in a "starved" basin, in which subsidence was more rapid than sedimentation. The uniformity and apparent slowness of deposition are in harmony with this interpretation. If the section is as complete as stratigraphic relations suggest, rates of sedimentation for

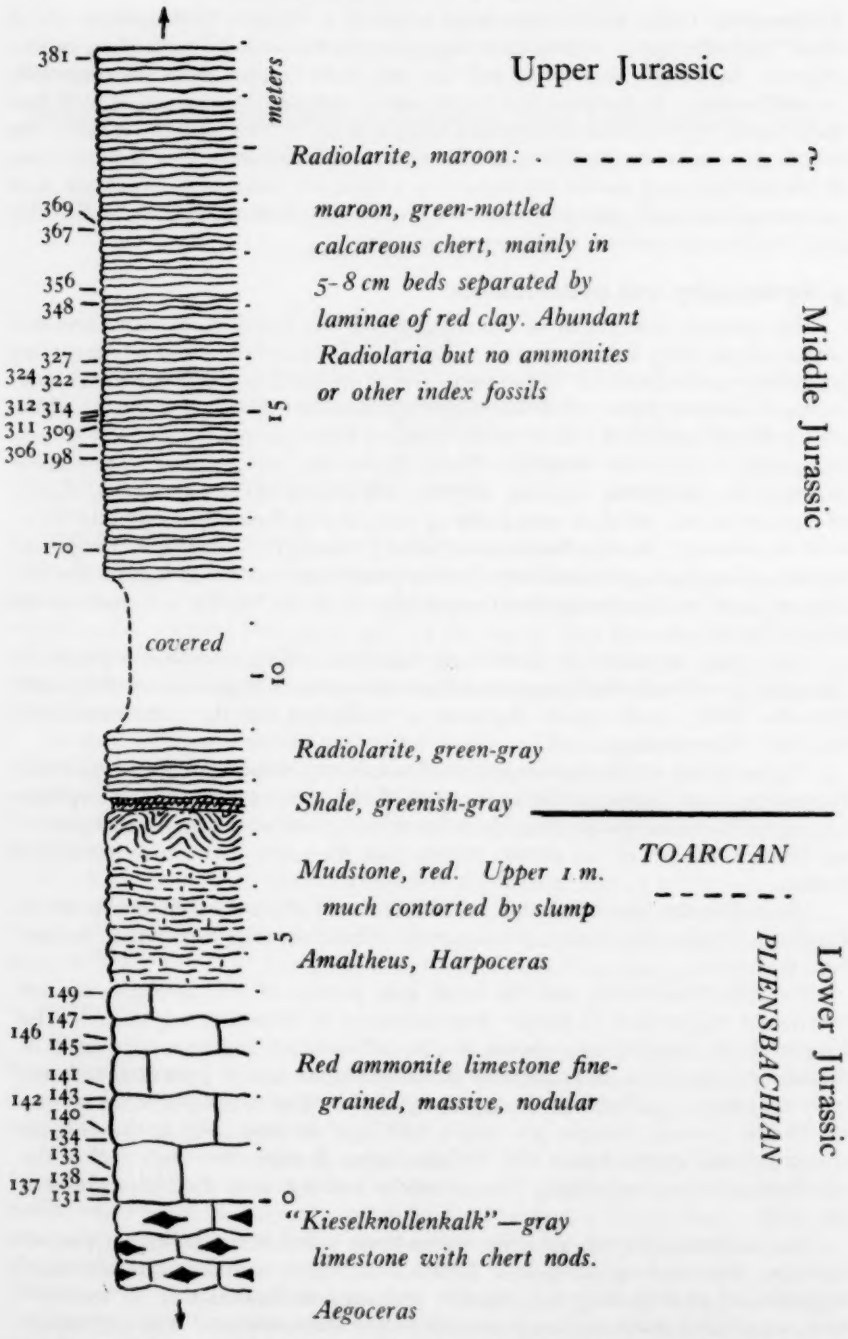

FIG. 1. Stratigraphic section on the west face of the Scheibelberg. Numbers at the left refer to oriented samples analyzed for remanent magnetism.

the red limestone were of the order of a hundred thousand years per metre, those for the radiolarite of the order of a million years per metre.

4. Remanent magnetism

The remanent magnetism of these red rocks is weak, the limestone averaging $4{\cdot}4 \times 10^{-7}$ emu/cm^3, the radiolarite, $10{\cdot}4 \times 10^{-7}$ emu/cm^3. The direction of magnetization is normal, pointing to a North Pole in the northern hemisphere. The measurements are summarized in Tables 1 and 2, and in Figures 2 and 3. They fall into two groups—one containing the Lower Jurassic limestones, the other the Middle Jurassic radiolarites—which overlap by about 50 per cent of their spread.

Within each group there is a distinct clustering of points in the mid-section. Otherwise, distribution of readings within the groups is random, bearing no relation to the detailed position of cores within the limestone or within the radiolarite. Differences in readings on twin cores cut from the same field sample range up to between a quarter and a third of the total spread. Pole positions, as determined by the average for each group, are shown in Table 2, and lie as follows: Lower Jurassic pole east of Lake Baikal; Middle Jurassic pole in the Aldan region, south of Yakutsk.

5. Discussion of pole positions

The magnetic results obtained are remarkably consistent when compared with the scatter generally obtained in the study of red siltstones and lavas. In view of the short-term gyrations of the pole and of a series of introduced errors—from the field orientation of samples to the cutting in the laboratory and to errors in final measurement—a greater consistency is hardly to be expected. Our samples show none of the magnetic instability observed by Creer (1957) in fine-grained red Keuper marls; on the contrary, they show that some fine-grained haematite-bearing, magnetite-free red sediments constitute exceptionally suitable subjects for palaeomagnetic investigations.

The pattern of polar wandering indicated by European palaeomagnetic data, enabled Irving (1958) to interpolate a Jurassic pole between Triassic and Eocene poles determined from Britain. The position of this interpolated Jurassic pole is about latitude 60° N, longitude 131° E. Our mid-Jurassic pole determination of latitude 58°·5 N, longitude 128° E, agrees closely with this prediction.

6. Origin of remanent magnetism

X-ray diffraction studies of the radiolarite and of insoluble residues of the limestone, indicate that haematite is the only potentially ferromagnetic mineral present. The haematite occurs as an extremely fine-grained red pigment; all attempts to concentrate it by physical methods were unsuccessful.

Three hypotheses may be advanced to account for the origin of the haematite and thereby the remanent magnetism shown by these rocks: (1) *primary*, (2) *penecontemporaneous* (early diagenetic), or (3) *epigenetic*.

(1) *Primary*. According to this hypothesis, the haematite particles originated in lateritic soils on the mainland or on islands within the Tethyan seaway, were carried by air or water currents and were deposited mechanically. Possessing a stable remanent magnetism acquired in or inherited from the source area, the

Table 1.

Magnetic Vectors of Samples

Stratigraphic position of the samples is shown in Figure 1. A, B and C denote distinct field samples taken in close proximity; a and b denote twin cores taken from the same field sample.

Sample No.	Azimuth	Inclination	
381a	50	37	
b	49	39	
369a	22	50	
b	25	50	
367	22	56	
356a	34	49	
b	32	52	
348a	15	47	
b	17	41	
327	42	49	
324a	27	51	
b	25	46	
322	28	43	
314	42	48	↑
312a	38	45	
b	40	50	Radiolarite
311	26	49	
309	37	38	
306	32	49	
198	32	49	
170	46	58	
149a	60	54	
b	65	63	
147	56	60	
146a	38	56	
b	38	52	
145a	29	49	
b	29	47	↓ Limestone
143a	44	56	
b	48	43	
142	27	56	
141	49	31	
140C	32	59	
140Ba	43	51	
b	40	53	
140Aa	41	48	
b	37	47	
134a	58	59	
b	61	52	
133a	42	45	
b	49	56	
138Ba	46	42	
b	34	39	
138Aa	44	41	
b	44	42	
137a	44	50	
b	45	45	
131a	53	55	
b	47	53	
120a	44	50	
b	41	42	

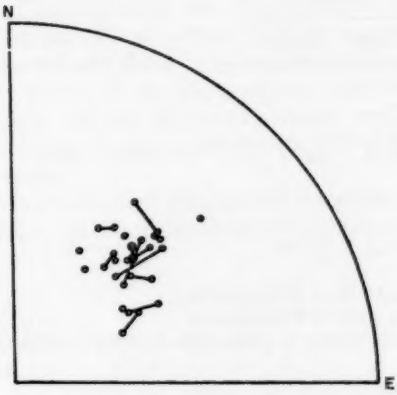

FIG. 2. Equal-area net plot of Mid- Jurassic (radiolarite) samples.

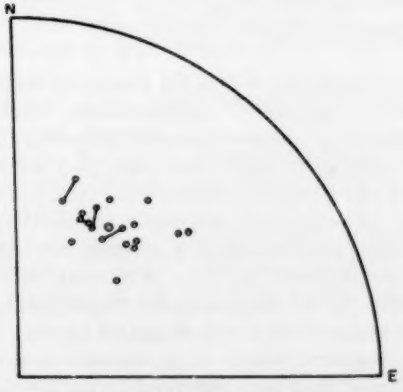

FIG. 3. Equal-area net plot of Lower Jurassic (limestone) samples.

○ Magnetic reading of one core.
⊙ Two superimposed readings from different cores.
Twin cores cut from the same field sample.

Table 2

Summary of Magnetic Results.

Point of observation: latitude 47°37′ N, longitude 12°34′ E.

	N.R.M.			Semi angle of cone of 95 per cent confidence	Pole position	
	Average azimuth	Average inclination	k of K		Lat.	Long.
					N	E
Radiolarite[1] (Mid-Jurassic)	36°·7	47°·8	100	5°·5	58°·5	128°
Limestone[2] (Lower Jurassic: Pliensbachian)	47°·9	50°·6	70·7	6°·5	53°	112°

(1) based on 21 cores from 15 field samples
(2) based on 30 cores from 16 field samples
Statistics calculated according to procedure recommended by Fisher (1953), Watson & Irving (1957).

particles became oriented in the Earth's magnetic field while settling and thus imparted a primary magnetic fabric to the sediment.

(2) *Penecontemporaneous or early diagenetic.* Another possibility is that the iron reached the site of deposition in solution and was there chemically precipitated. The haematite particles could have formed directly, or been developed during the process of diagenesis (e.g. dehydration of goethite). In either case the remanent magnetism, acquired *pari passu* with sedimentation, would be of chemical origin, the result of crystallization within the Earth's field. The existence of such a "chemical remanent magnetism" has been suggested by Martinez (1956), Howell & others (1958), and demonstrated by Nagata (1958).

(3) *Epigenetic.* A third possibility is that the haematite may be of late diagenetic origin, with an equivalent "epigenetic" magnetization. Alternatively, a haematitic sediment of either primary or penecontemporaneous origin may have received a secondary magnetic overprint at some later time as a result of metamorphism, electrical discharge, or some other undetermined factor.

In the case of the rocks studied, epigenetic magnetization appears the least likely of the three possibilities; haematite is magnetically highly stable; the rocks show no signs of metamorphism, no trace of flowage or cleavage. They were quite possibly overridden by the Berchtesgaden thrust sheet, but may never have been buried to depths greater than 3 or 4 thousand metres. Moreover, epigenetic magnetization of late diagenetic origin, or in response to temperature changes or orogenic events would most likely have occurred during late Cretaceous or Tertiary time, and should in that case have imparted a magnetism more nearly like the Earth's present field than that observed.

It therefore appears that the magnetism encountered is either a primary (physical) or early diagenetic (chemical) type, or possibly a combination of both. For practical purposes there should be no difference, since both types should essentially reflect the magnetic field existing about the time of deposition.

7. Conclusions

1. Red limestones and maroon radiolarites, of Lower to Middle Jurassic age, from the northern calcareous Alps, have been analyzed for remanent magnetism. The rocks are exceedingly fine-grained, and the magnetic mineral present is haematite.

2. The magnetic vectors obtained are comparatively consistent, and show no reversals. A lower Jurassic (Pliensbachian) pole is suggested at latitude 53° N, longitude 112° E (east of Lake Baikal), and a Middle Jurassic pole at latitude 58°·5 N and longitude 128° E (in the Aldan region, south of Yakutsk).

3. The Mid-Jurassic position agrees remarkably well with a Jurassic pole position predicted by Irving, based on extrapolation from British data on Triassic and Eocene pole positions.

4. The results indicate that very fine-grained haematite-bearing magnetite-free sediments may be more reliable palaeomagnetic indicators than the typical red siltstone or lava.

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Research Note

The Reduction of Gravity Observations

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Summary

The values of the Earth's ellipticity given by artificial satellites and by the analysis of gravity differ by about three times the standard error. Investigation of the possible effects of non-orthogonality between P_2, P_3 and P_4 in the normal equations suggests that allowance for it would not multiply the standard error by more than 1·1, and that the explanation is more likely to lie in the comparison of base stations.

The method of weighting used in the determination of the geoid by Heiskanen is criticized as leading to serious systematic error.

1. Observations of artificial satellites have led to an estimate of the Earth's ellipticity of about $1/(298{\cdot}1 \pm 0{\cdot}1)$. $1/e$ deviates by about 1·0 from my solution based on numerous types of data. The most accurate single determination was from the precessional constant, even after allowance for probable departures from the hydrostatic state. What is more remarkable is that the estimate with the next smallest apparent uncertainty, that from the analysis of gravity, gave (Jeffreys 1942a, p. 65)

$$1/e = 296{\cdot}17 \pm 0{\cdot}68$$

and the coefficient of P_2 in gravity was $3\,439{\cdot}9 \pm 5{\cdot}0$ mgal. The discrepancy is nearly three times the standard error and invites discussion on the validity of the estimate of uncertainty.

The most doubtful point of the analysis is the treatment as random of all variation of gravity except the terms that showed up as possibly significant in the preliminary analysis. This was illustrated (Jeffreys 1941, p. 4) by considering n observations uniformly distributed over the northern hemisphere, analysed for a constant and terms in P_2, P_3 and P_4. If these are small compared with the error of one observation, the true standard error of the coefficient of P_2 is 4·2 times that found by neglecting P_3 and P_4. But in the solution these terms were in fact neglected.

The total weight in the northern hemisphere is taken as 32 and that in the southern as 10; these are in nearly the ratio of the actual weights. Then the matrix of the coefficients in the normal equations is 32 times that at the top of p. 4 together with 10 times the matrix with the signs of the non-diagonal elements corresponding to P_3 reversed. It is then

a_0	a_2	a_3	a_4
42	0	−2·75	0
0	8·4	+2·75	0
−2·75	+2·75	6·0	+1·55
0	0	+1·55	4·67

Expressions with independent uncertainties are, with their weights,

$a_0 - 0{\cdot}065\,a_3$	42 ;
$a_2 + 0{\cdot}33\,a_3$	8·4 ;
$a_4 + 0{\cdot}33\,a_3$	4·67 ;
a_3	4·38 ;

If the standard error for unit weight is 1, $\sigma^2(a_2)$ is 0·145, and that found if a_3 and a_4 are rejected is 1/8·4; the ratio is close to 1·2. The difference from the result found previously is a consequence of the observations in the southern hemisphere, which practically halve the non-diagonal coefficients in comparison with the diagonal ones. The standard error of the coefficient of P_2 will be 5·5 mgal.

A rough analysis indicated (Jeffreys, 1943 b, p. 88) that the expectation of the mean square of the deviation of gravity due to a third harmonic not already detected would be about 2·7 mgal^2. The coefficient of a real term in P_3 might be taken as $\pm(7\times 2{\cdot}7)^{\frac{1}{2}}$ mgal $= \pm 4{\cdot}4$ mgal. Then the error introduced into the coefficient of P_2 by the assumption of orthogonality might be $\pm 1{\cdot}5$ mgal. This would make the standard error of the coefficient 5·2 mgal.

It appears that allowance for non-orthogonality will not account for the discrepancy between the results from gravity and artificial satellites, which will remain at about 2·7 times the standard error.

In any case my analysis needs revision, largely on account of improved comparisons of base stations. But it has seemed worth while to point out that the effect of non-orthogonality, in possibly its worst case, is not so serious as might have appeared.

2. The remarkably low apparent uncertainty of the Sputnik estimate is of course an invitation to look for systematic errors. Harmonics other than zonal ones could produce no secular effect on the motion of the node, but it seems worth while to call attention to a possible effect of air resistance. King–Hele makes a comparison of values of $d\Omega/dt$ for three different stages in the motion of Sputnik 2, and the ratios of observed and calculated values agree. This would suggest that the atmosphere does not affect the ratio, since the orbit in fact changed considerably in other respects. But this is not quite obvious. If the air was at rest the resistance could not affect the motion of the node. But since it moves with the Earth (a little faster in the stratosphere) we might expect it to reduce the longitude from node to node for a satellite travelling west, and to increase it for one travelling east. It is desirable that a comparison should be made.*

* Examining this matter later I found that for a circular orbit there would be an effect on the inclination but none on the node; but King-Hele tells me in a letter that when the resistance is mostly near perigee the effect on the node may be considerable.

3. A rediscussion with more modern data is by Heiskanan (1957). As a result of a discussion by Hirvonen (1956) a different system of weighting is used, which seems to me to be entirely erroneous. Hirvonen notices that the correlation of gravity residuals falls off rapidly with distance; he remarks that "if there is only one observed station inside a square with side 2°·6 it is better to put the anomaly of the square equal to zero than to use the observed anomaly as representative of the square. However the best value obviously is the weighted mean of them both (observed value and zero . . .)" This amounts to saying that it is best to assume no correlation of anomalies at distances over 2°·6 and that without observations within this distance it is best to use the trial form of gravity, which we are trying to correct, as accurate. But if there is a term $P_2^2 \cos 2\lambda$ in gravity it produces positive correlations up to 90° separation, and it is clear from Heiskanen's map that there are runs of constant sign in the 10° means for many consecutive squares. In fact the hypothesis is contradicted by the conclusion. If such terms are not ruled out as *a priori* impossible the "anomaly" must be reinterpreted; it is simply the difference between observed gravity and the estimate from the trial solution. Heiskanen remarks in relation to a solution by Zhongolovitch that it gives undulations of the geoid on an average 2·5 times larger than the gravity observations permit. My comment would be that this is the factor by which the Heiskanen–Hirvonen solution makes them too small by taking a bad first approximation as a definitive solution.

Hirvonen's weights make the solution a weighted mean of the trial solution and the solution given by the observed values alone. Call this solution 1. If we are prepared to make any change from the trial solution, we must take solution 1 as a new trial solution and repeat the process; we get a new set of corrections, giving solution 2. So long as the observed values alone give a larger coefficient for a harmonic than the trial solution, the next approximation will increase it. The solution can repeat itself only when it has become identical with that given by the observed values alone.

Kaula (1958) comments that in my solution there is a negative correlation in my reductions between the number of 1° squares represented in a 10° square and the absolute value of the estimated standard error, and attributes it to my use of the direct mean. He omits to mention that I eliminated the systematic variation with height by a linear formula. The actual reason is that most of the regions of great variation of the gravity anomalies are of much less width than 10°, and are also regions where the free air anomaly shows greater departures from a linear variation with height.

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Notes on progress in Geophysics

Current Research in Geophysics in Canada

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Introduction

Geophysical research in Canada is carried on by Government laboratories, at least half-a-dozen universities, and to some extent by companies who are applying geophysical methods in exploration programmes. The International Geophysical Year has seen a great increase in activity, especially in those disciplines for which the Year was primarily intended, such as meteorology, upper atmosphere physics, and oceanography. In fact, the over-all activity in these fields is almost too extensive to summarize in a review which includes the physics of the solid Earth as well. For this reason the present article deals primarily with recent developments in the latter field. It is, of course, difficult as well as dangerous to attempt to draw too sharp a distinction, as, for example, in the case of short-period variations in the magnetic field, which have a source outside the Earth but are influenced by the conductivity within. However, the discussion which follows is not intended to be an exhaustive catalogue of all work in certain specific fields. Rather it is an outline of those developments which appear, to the author, most promising in furthering our understanding of the behaviour of the Earth's crust and of the deeper interior.

Seismology

A network of seismograph stations, extending from Halifax to Vancouver and north to Resolute Bay on Cornwallis Island, is operated by the Dominion Observatory. Many of these stations contain three-component instruments, and some are equipped with seismographs of both long and short periods. The instruments have recently been calibrated for amplitude by an impedance bridge method, and the network is now probably one of the most extensive for which a uniform calibration is available.

A major programme of research in seismology at the Observatory has been the determination of the direction of faulting in earthquakes, from studies in the first motions recorded at stations distributed over the Earth (Hodgson 1958). The distribution of initial compressions and rarefactions in the *P*-arrival allows the orientation of the fault plane, and the direction of motion along this plane, to be determined with one degree of ambiguity. If the initial motion on *S* is studied, this ambiguity is removed. The most important result of this work is that the greater part of the motion in the earthquakes studied is horizontal and strike-slip or transcurrent. This appears to be true regardless of the depth of focus of the earthquake, and is in contrast with the type of motion predicted in most theories of mountain building. The patterns of faulting direction which have been found in various active areas are not yet completely understood, but they will undoubtedly prove useful in further studies on the failure of the crust.

During 1958, there were two important opportunities in western Canada to study crustal structure by means of blasts. The first of these, in April, was the removal of the top of Ripple Rock, in Seymour Narrows between Vancouver Island and the mainland of British Columbia. The blast consisted of the detonation of over 1 300 tons of explosive packed into tunnels excavated in the solid rock. This was recorded at a series of stations, both permanent and temporary, in a line across the mountains into the prairies. Many of these were operated by the Dominion Observatory, which co-ordinated the seismological application of the blast, but others were provided by university groups and commercial geophysical parties. An interesting example of the co-operation provided for the recording was the broadcasting of standard one-second time signals by all stations of the Canadian Broadcasting Corporation, which gave all recorders the advantage of precise timing. Preliminary interpretations of the records, which were obtained at Canadian stations up to 600 miles from the blast, indicate a thickening of the crust beneath the Cordilleran Mountains by roughly the same amount as suggested by gravity measurements.

In order to provide control for the eastern end of the Ripple Rock profile, experiments were made in May with two blasts, of 900 lbs. each, fired near Calgary in the plains. These blasts were arranged and recorded by a group of commercial geophysical and oil companies. The explosions were at either end of a line, eighty-one miles long, which was roughly parallel to the mountain front to the west. Along the line, spreads of conventional exploration equipment consisting of relatively low-frequency refraction geophones and recorders were laid out. The experiment differed from previous work with blasts in this country in the density of observing points and in the natural frequency of the seismometers. Many of the individual spreads contained twenty-four detectors, and the average natural frequency was 7 cycles per second, in contrast to the 1-second seismometers often used. Excellent records were obtained of refracted arrivals from the base of the crust, the refractions merging with the critical angle reflection at the appropriate distance. A most interesting feature was a distinct arrival corresponding to the wave refracted along the Conrad discontinuity within the crust. The depths obtained were 29 km and 43 km for the Conrad and Mohorovičić discontinuities respectively (Richards & Walker 1959). The figure for the thickness of the crust was rather greater than had been expected, for the location was well to the east of the front of the foothills, with a surface elevation of about 3000 feet. The geometry of the blasts and recording stations allowed the dip of the discontinuities to be estimated, and the Conrad discontinuity was found to dip three degrees toward the south. The Mohorovičić discontinuity appeared to be horizontal, although a longer line would have been desirable to confirm this.

Gravity

The national network of primary gravity stations, and the connection of this network to those of other countries, are responsibilities of the Dominion Observatory. More local surveys to study the effects of geological structures are also carried out by the Observatory, and by university groups. Recently, the connections of the national base at Ottawa to both Washington and Paris have been improved by gravity meter measurements. The connection to Paris was made by direct flights to and from Gander, Newfoundland. This pair of stations is very suitable for trans-Atlantic measurements, as the values of gravity differ by only a few milligals.

Within Canada the range in gravity encountered from south to north makes the calibration of gravity meters over different parts of their range an important problem (Innes 1958, Gilbert 1958). For this purpose, stations have been established along north-south lines with different types of pendulum apparatus. At present the Observatory is using bronze pendulums, maintained at constant temperature by thermostats, swung in pairs and timed by a crystal clock. These pendulums, which are over forty years old, appear to have reached a satisfactory degree of stability.

Perhaps the greatest contribution that has been made in gravity measurements for structural studies has been in the study of effects observed over the exposed Precambrian shield. These studies have shown the mass distributions to be expected in typical rocks of the continental crust, without the masking effect of overlying sedimentary rocks. Rather intense anomalies have been observed in areas of low relief, and these, whether the result of broad regions of anomalous density or of variations in crustal thickness, appear to date from eras of Precambrian mountain building. It is obviously important to extend those areas for which both gravity observations and seismological evidence on crustal thickness are available. The agreement between the seismological and gravitational estimates of crustal thickness beneath the Cordilleran mountains is encouraging in this regard. The University of Toronto group have made detailed measurements over the Grenville province of the shield, while the University of Alberta has traced, by gravity measurements, Precambrian features beneath the sedimentary basin and into the Rocky Mountains. It has been possible to find evidence of the dislocation of the covered shield as a result of the younger mountain thrusts (Garland & Burwash 1959).

For a number of years there has been speculation on the amount of uplift, still in progress, of the northern part of the continent following the disappearance of the Pleistocene ice sheet. Certainly the gravity anomalies appear to be too greatly influenced by structure for any over-all negative tendency, which might be related to crustal depression, to be found, at least with the present distribution of stations. The recent establishment of tide gauges at Resolute Bay on Cornwallis Island, and at Frobisher Bay on Baffin Island should be of great assistance in determining the existence of continuing uplift of the land. Two additional gauges, at Coppermine and Taktoyaktuk on the Arctic coast of the mainland, are to be installed in 1959.

Terrestrial magnetism

As in other fields of geophysics, geographical location appears to have influenced trends in geomagnetic research in this country. For example, until quite recently, more emphasis has been placed on the mapping of the field to aid on the location of the pole, and on the nature of magnetic disturbance in the auroral zone, than on palaeomagnetic measurements.

Magnetic field measurements for the construction of charts have been greatly assisted by the three-component airborne magnetometer of the Dominion Observatory (Serson & others 1957). The instrument consists of three mutually perpendicular saturation core detectors, which are kept in orientation by a gyroscopically stabilized platform. It has been flown over considerable areas of the country, and also over the parts of the Atlantic and Pacific Oceans, where the magnetic field elements have been imperfectly known.

Magnetic variations in northern latitudes (Whitham & Loomer 1958) are recorded at the permanent observatories, Baker Lake and Resolute Bay, and also

at a number of temporary observatories established for the International Geophysical Year. These observations have been used for investigations at the Universities of Toronto and British Columbia on the current systems (Jacobs & Obayashi 1956) which could produce the effects. The observing stations are rather well distributed for studies of both regular variations and magnetic storms, for they include points south of, in, and north of, the belt of greatest auroral activity.

A related field which is currently of considerable interest is the study of short period variations in the magnetic components. These variations include effects with periods from a few minutes to, say, 0·01 seconds. The Pacific Naval Laboratory is studying the areal uniformity of the variations over parts of Western Canada. At the University of Alberta, the correlation between the magnetic variations and the related earth currents is being studied. It is known that the local conductivity affects the character of the magnetic disturbance, and there is hope that broad applications to the study of geological structures can be found.

The use of measurements of the total magnetic field for the outlining of structure has been greatly assisted by the aeromagnetic programme of the Geological Survey. The results of surveys by this group are published on map sheets at a scale of 1 inch to 1 mile, and there is now a very complete collection of these showing the distortions of the magnetic field produced by different types of structures. While a primary purpose of the aeromagnetic surveys is for commercial reasons, they can be very useful for fundamental studies, as, for example, in pointing out masses of rock which are inversely magnetized.

Measurements of the natural remanent magnetization of rocks are being made by the Geological Survey, Dominion Observatory and various universities. Emphasis has been placed on Precambrian samples, especially from formations for which the absolute age is known from radioactive measurements. The aim, of course, is to determine with more certainty the movements of the magnetic poles in Precambrian time, which includes such a large proportion of Earth history. At the University of Western Ontario, the magnetic properties of ilmenite-bearing samples are being correlated with their petrological characteristics. Ilmenite, which plays an important role in certain cases of reversed magnetization, occurs in many intrusive igneous rocks in eastern Canada. Theories of mountain building which include the continental drift suggested by palaeomagnetism are being examined (Scheidegger 1957).

Other branches of Earth physics

Age determinations by radioactive methods are in progress at the Geological Survey and the Universities of Toronto and Alberta, while a new mass-spectrographic laboratory is being set up at the University of British Columbia. The methods that have been chiefly used to date are based on the various uranium–lead series, and on the potassium–argon ratios. At the University of Toronto, emphasis has been placed on the dating of events in Precambrian time, as a result of which the Shield has been divided into provinces of different age. At Alberta, Precambrian rocks encountered in deep drill holes, as well as younger rocks from the western mountains and plains, have been studied. The potassium–argon method can be applied to rocks as young as late Tertiary (Lipson 1958), in spite of the very small concentration of radiogenic argon, but the ability of different minerals to retain argon is a critical factor. Research on the diffusion of argon through different lattice structures is in progress. The dating method based on the decay of rubidium

into strontium has the great advantage that no gaseous state is involved, and all of the groups mentioned are preparing to investigate this method.

Apart from the measurement of geological age, the determination of isotope variations in minerals is important for indicating the conditions under which the minerals were formed. At the University of Toronto a collection has been made of all of the lead isotope ratios that have been made on deposits in various parts of the world. Lead ores of a given age may have ratios "normal" for the age, or "anomalous" under certain conditions of formation of the deposit (Russell & others 1957).

Measurements of the flow of heat from the interior of the Earth are being made by the universities of Western Ontario (Beck & Beck 1958) and Alberta. At the former, a probe for the measurement of thermal conductivity *in situ*, and a temperature gradiometer for use in bore holes, are being developed. At Alberta, temperature gradients are being measured in abandoned oil wells, while the thermal conductivities are measured on core samples from these holes. In both cases the aim is to provide a more complete distribution of heat flow values over the continent.

A region that requires particular investigation is the Arctic, where the Western Ontario group have measured the very high value of $2{\cdot}9 \times 10^{-6}$ cal/cm^2 s at Resolute Bay (Misener & others 1956).

Research on the physical properties of glaciers was not actively pursued in Canada until the beginning of the International Geophysical Year. Since then, the Salmon glacier in the Cordillera, and the icecap on northern Ellesmere Island have been studied in detail. The measurements have included the determination of ice thickness by seismic and gravity methods, the mapping of the boundaries of the ice for future comparisons, and the study of the energy budget by micrometeorological observations (Adkins 1958).

It is encouraging to note that many of the programmes started as I.G.Y. projects will be continued on a more permanent basis. This applies, for example, to the work in glaciology and to at least some of the magnetic observatories. It is also of interest to point out the co-operation between government, university and commercial groups on such important projects as the Ripple Rock recording. In a country where the geophysical population is spread rather thinly, such co-operation plays an important part in research.

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Palaeomagnetic Pole Positions: A Survey and Analysis

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Summary

The positions of the pole during different geological periods obtained from studies of the magnetism of rocks are reviewed. For the past 20 million years the results from different continents are in good agreement. For periods prior to this, the results from the same continent are still in broad agreement with one another but not with those from different continents. The meaning of this disagreement is discussed and it is concluded that explanations other than relative movements between continents (continental drift) are not promising.

1. Introduction

Most of our information about the Earth's magnetism has been obtained by direct observation over the past four hundred years. In principle, the study of the magnetism of rocks provides the means to extend this record back into the remote geological past since some rocks became permanently magnetized parallel to the Earth's field at about the time they were formed. Thus, by measuring these directions in the laboratory the behaviour of the field in the past can be investigated, but there is the disadvantage that the observations are indirect and there are many uncertainties. The reversals of magnetization in rocks indicative of periodic reversals in the field first attracted attention, but about four years ago palaeomagnetic results were used from the Tertiary by Hospers (1955) and from older periods by Creer & others (1954) to compute the position of the geomagnetic pole at these times, thereby fulfilling a prediction by Mercanton in 1926 that the study of rock magnetization could lead to investigations of polar movements. In recent years many workers have devoted their attention to defining the positions of the pole in this way and over one hundred results are now available from different countries. The principles of this aspect of palaeomagnetism are discussed in Sections 2 and 3, and an atlas of polar positions for different geological periods follows in Section 4. The significant features of the results are explained in Section 5, and in Section 6 there is a discussion of one of the most important of these, namely, the lack of agreement between results from different continents in pre-Miocene times.

2. Origin of the remanent magnetism in rocks

A rock which becomes permanently magnetized in the direction of the Earth's magnetic field at the time it is formed is said to have acquired a *primary* magnetization. Long after formation further components may be added modifying or obliterating the primary one and such rocks are said to possess a *secondary* magnetization. There are four principal ways in which a rock may acquire a permanent moment.

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Thermo-remanent magnetization. For any substance containing ferromagnetic minerals of uniform grain size and composition it is possible to define the relaxation time τ at a given temperature, τ being the time required for the magnetic moments to approach equilibrium with an applied field (Néel 1955). At temperatures very near the Curie point τ is very short, but it increases as the temperature falls and at normal temperatures becomes very long. Thus, an igneous rock which has cooled through its Curie temperature becomes magnetized parallel to the Earth's field and retains this direction of magnetization against subsequent changes in direction of the field provided τ exceeds its geological age. This is called thermo-remanent magnetization which is generally abbreviated to T.R.M.

Detrital magnetization. In sedimentary rocks the iron minerals are either detrital or chemical in origin and depositional processes or subsequent chemical activity may be responsible for the primary magnetization. Detrital ferromagnetic minerals are rock or crystal fragments usually of magnetite or specular ore which have been derived from pre-existing rock formations from which they may have inherited remanent magnetic moments. The conditions of deposition will affect the alignment of these particles as they become incorporated into the sediment, and in some cases, notably in the Torridonian Sandstone Series (Irving 1957) the dispersion of directions observed is much less in find-grained sandstones laid down under tranquil conditions than in coarse sandstones deposited in turbulent water (Figures 2 and 3), but the mean direction is the same. Sedimentary rock formations which have a predominantly detrital magnetization do not appear to be common, the best examples being the Quaternary varves (Johnson & others 1948, Ising 1942, Griffiths 1955, King 1955) and the Torridonian Sandstone Series. Buff, green and grey sediments which contain detrital iron minerals are usually found to have a weak secondary magnetization unrelated to the earth's field at the time of deposition (Nairn 1957b).

Chemical magnetization. Iron minerals formed by chemical activity in sedimentary rocks usually occur as iron oxide cement, or as coatings to the non-ferromagnetic detrital particles, or as fine iron oxide dust spread through the rock. At the time it is deposited it may become magnetized in the direction of the magnetic field (Martinez & Howell 1956, Doell 1957). Since these chemically deposited iron minerals are incorporated in the rock after deposition of the detrital non-magnetic mineral particles there is no dependence of dispersion on the grain size of the latter. The most important rock types of this category are the red beds usually associated with deposition in a hot desert environment, red and black haematitic limestones and red tuffs. Haigh (1958), who has demonstrated the efficacy of chemical magnetization in the laboratory, suggests that the mechanism by which chemical magnetization occurs is as follows. The relaxation times of minerals is low when their particle size is very small and such grains representing the initial phase of chemical deposition could become magnetized by the earth's field. As these small nuclei expand by crystal growth τ increases and a permanent magnetization not unlike T.R.M. is built up. The variable in this process is grain size, whereas in T.R.M. it is temperature.

Isothermal remanent magnetization (*I.R.M.*). For any magnetic mineral τ depends on grain size. Since the iron mineral assemblage in a rock specimen may contain a considerable range of particle sizes and chemical composition a wide range of

relaxation times may be represented so that the observed direction of the remanent moment will be the vector sum of primary and secondary components. Some success has attended efforts to remove the latter by "washing" specimens in alternating magnetic fields (Rimbert 1958, Creer 1958) or heating followed by cooling in zero field (Doell 1956, Cox 1957).

In general T.R.M. is responsible for the primary magnetization of igneous rocks. In sedimentary rocks the primary magnetization is detrital or chemical in origin. Between the period of formation and the present day the rock may become remagnetized by the process of I.R.M., or by T.R.M. if reheated above the Curie temperature, or by chemical magnetization if new minerals are deposited in the rock. Thus in thermally metamorphosed rocks the original magnetization will be replaced by a T.R.M. identifiable with the Earth's magnetic field at the time of metamorphosis. In rocks which have undergone metasomatic changes below the Curie point chemical magnetization is likely to be operative. This is of some interest since it should be possible to distinguish between granitized sediment and truly magmatic granite since the former is likely to have a chemical magnetization and the latter a T.R.M.

Figures 1 to 7 illustrate results from rocks which have acquired their magnetization in different ways. North-seeking directions are shown as dots or circles intersecting the lower and upper hemispheres respectively. Declinations are measured clockwise from geographic north. In Figures 1, 4, 5 and 7 the plane of projection is the present horizontal, which, since the rocks concerned are not tilted, corresponds to the horizontal at the time of deposition. In Figures 2, 3 and 6 the plane of projection is the bedding plane, so that the directions are corrected for folding. Figure 1 (Irving & Green 1957) shows the directions in a lava flow with T.R.M. Figures 2 and 3 illustrate detrital magnetization in sediments. The effect of chemical weathering is illustrated in Figures 4 and 5. The directions in unweathered pinkish-brown sandstone which is hard and compact are towards the south-west with shallow negative inclinations, whereas those in weathered sandstones from the *same* formation are clustered around the present axial dipole field. The weathered rock is bright red, friable and highly porous, and has undergone chemical weathering in some cases to a depth of several hundred feet during the Cenozoic. The iron minerals present in the fresh sandstone have been reconstituted and there has been a good deal of iron enrichment. A further case of chemical magnetization is illustrated in Figure 6 which shows the directions in some Carboniferous red tuffs. Their colour is due to haematite dust which is responsible for the magnetization and which was probably excreted as a by-product of devitrification of volcanic glass (Coombs 1958). Lastly, Figure 7 illustrates the effect of a secondary isothermal magnetization superimposed on a primary magnetization (Creer 1957b). The directions fall in the plane containing the primary direction and the present dipole field.

3. Geomagnetism and palaeomagnetism

Mathematical analysis ascribes the Earth's field to hypothetical multipoles at the geocentre (Vestine & others 1947). The lowest order multipole, or dipole, has three components, one along the axis called the geocentric axial dipole which is by far the largest, and two of much smaller value in the equatorial plane. The higher-order multipoles are small in magnitude compared with the geocentric axial dipole. Changes affecting the geomagnetic field are of four main types each with characteristic periodicities: the transient and secular variations which have

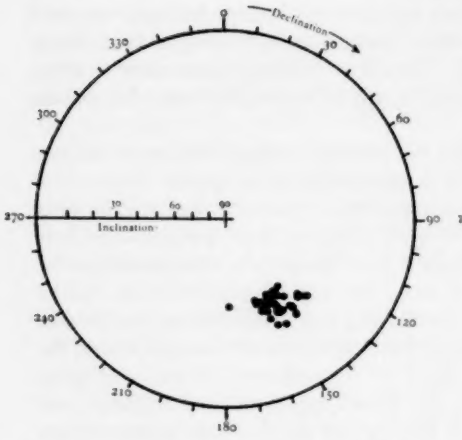

FIG. 1.—*Directions of magnetization in a Cenozoic lava flow.* Directions in samples taken from a quarry (Adam's Quarry, Alphington, Melbourne, Australia) in the Newer Volcanics of Victoria. The stereographic projection is used in this and in Figures 2 to 17.

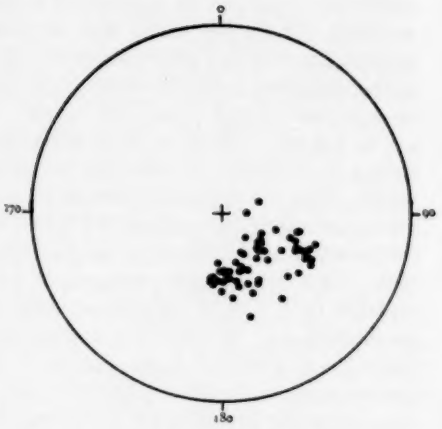

FIG. 2.—*Directions in very fine sandstones.* These specimens were collected from the Aultbea Group of the Torridonian Sandstone Series, Scotland. The specimens are spaced through a section 75 feet thick on the shore near Laide, Rosshire. The age is Upper Pre-Cambrian.

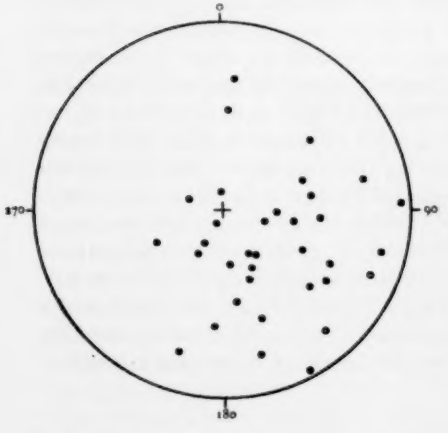

FIG. 3.—*Directions in coarse-grained current-bedded sandstones.* Results from the Aultbea Group of the Torridonian sandstone on Isle of Ewe, Rosshire. These specimens are from the base of the Group several hundred feet beneath the beds from which the results in Figure 2 were obtained. The directions are more scattered but the mean direction is the same as in Figure 2.

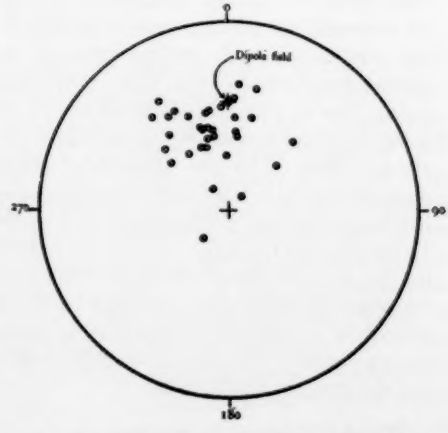

FIG. 4.—*Directions of magnetization from weathered Cambrian sandstone.* Elder Mountain Sandstone, northern Western Australia.

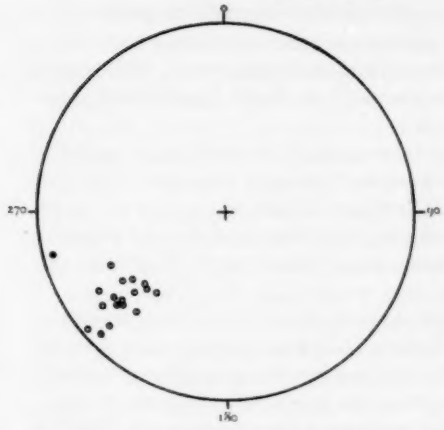

FIG. 5.—*Directions of magnetization in fresh Cambrian sandstone.* Elder Mountain Sandstone, northern Western Australia.

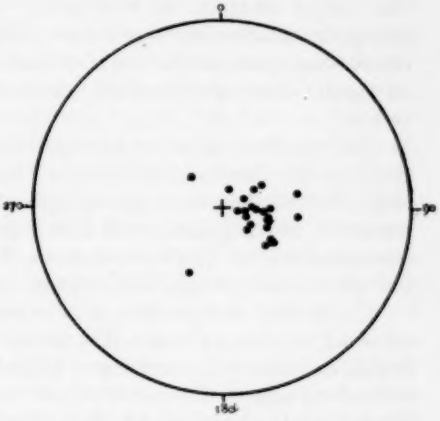

FIG. 6.—*Directions of magnetization in fine-grained red tuff.* Eagleton quarry, Seaham, New South Wales. Kuttung Series, Upper Carboniferous.

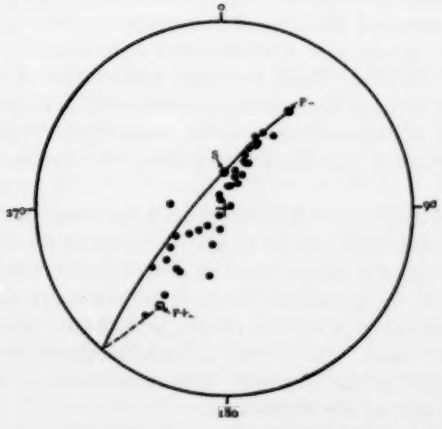

FIG. 7.—*Directions of magnetization in Triassic sandstones.* Sidmouth, England (after Creer 1957b). P^- and P^+ are the poles of the axis of primary magnetization obtained by Clegg & others (1954). The directions fall close to the plane containing this and the direction of the axial dipole field *S*.

their major effect on the non-dipole components, and reversals of polarity and change in attitude of the dipole field. The evidence for the first of these comes from direct observation and for the third and fourth from rock magnetism. Information on secular variation is derived from both sources but chiefly from direct observation.

The transient variations have periods of the order of days and have negligible effect on the direction of the field. The transient variations arise primarily from magnetic disturbances in the ionosphere (Chapman & Bartels 1951) whereas the remainder of the geomagnetic field is produced internally probably by electrical currents driven by fluid motions in the Earth's core (Elsasser 1956, Runcorn 1954, Bullard & Gellman 1954, Hide 1956).

The secular changes have angular amplitudes of about 10–20° and periods of the order of 10^2 or 10^3 years. The secular variation is represented by maps showing isopors or lines of equal change. Maps for the last few decades show a westerly drift of the isopors at a rate of 0°·3 of longitude per year (Bullard & others 1950). Thus, the field when viewed from the Earth's surface for 2 000 years or more should average to the geocentric axial dipole. This has been substantiated by palaeomagnetic studies (Figure 8) and has been the most important feature of the field at least during the past 10^6 years. If this has always been so the average direction of magnetization of a rock sequence which took several thousands of years or more to be formed will approximate to a line of force in the average dipole field, and, the poles or intersection of the dipole axis with the surface can be readily calculated and errors ascribed (Creer & others 1957).

In early work when averages through thick rock formations were taken (Creer & others 1954) polar wandering was represented as a steady drift of the dipole axis at the rate of 0°·3 of arc per 10^6 years, so that in the late Palaeozoic the pole was approximately 60° from its present position. This may be the smoothed effect of many small irregular polar jumps, and Green (1958) has shown that the polar data from Europe and the United States may equally well be represented as a random walk on a sphere with instantaneous velocities of 3° per 10^6 years, ten times the smoothed velocity. Thus, to obtain information about polar wandering it is necessary to eliminate the secular variation by averaging through a rock formation which was deposited over a period exceeding 10^3 years but if the period covered exceeds 10^6 years it is likely that some of the details of polar wandering will be lost.

Reversals of polarity occur within many rock formations (see Table 1 column 5). These could arise from self-reversal of the constituent ferro-magnetic minerals (Néel 1951, Nagata 1953), or from reversals of the Earth's field implying periodic reversals in polarity of the geocentric dipole (Hospers 1954, Allan 1958 and many others). Reversals appear to be sudden events, geologically speaking, being accomplished in about 10^4 years. They seem to have occurred about once every 10^6 years since the middle of the Tertiary. The occurrence of reversals creates an ambiguity as to the sign of the dipole axis.

The computation of pole positions has as its basis two assumptions; that in certain rocks the directions of magnetization reflect the ancient field direction, and that the field has averaged to a geocentric dipole. These assumptions, which are discussed in Section 6, are concerned with events long since past and by their nature can never be proved absolutely true or false. They have the merit that they lead to results which are internally consistent (see Section 6) and which are of some interest for geophysics and geology.

4. Palaeomagnetic pole positions

The pole positions obtained by this method are now reviewed in geological sequence. Numerical data are given in the table. In some cases the pole positions were not calculated by the workers who made the observations, and this has been done by the author. These cases are indicated by an asterisk * in the sixth column. Many results have been obtained from rock formations of substantial thickness so it can be reasonably supposed that the secular variation has been averaged out. Errors for these poles have usually been given, but there are cases in which the necessary numerical data has not been included in the original and these are indicated by question marks in the last two columns. Many results have been obtained from limited thicknesses, perhaps a single lava flow or a few feet of sediment. These are spot readings in time and will be subject to an unknown error due to secular variation and are indicated by dashes in columns 9 and 10. They are included for comparison with results from thicker sequences. Because of the drift of the dipole axis it is difficult to describe the polarity of the field in any consistent fashion. Runcorn (1955) suggests that dipole fields with the same sense as the present field relative to the axis of rotation be termed negative and opposed fields positive. This is satisfactory for Carboniferous and later pole results which lie in more or less connected sequences terminating at the present rotation poles. The distribution of earlier poles is however much more complicated and their identification with one or other of the geographic poles is arbitrary. The convention used here is to regard the field as negative (positive) when the pole towards which the north (south) seeking magnetization points is in the present day northern hemisphere. These polarities are recorded in the fifth column of the table. The poles for the northern hemisphere are plotted in Figures 8 to 17. The mean position is indicated by a dot and where possible is circumscribed by an oval within which the pole lay at $P = 0{\cdot}95$ (Creer & others 1957). The poles are identified by the numbers **1** to **112** always in heavy type, the numbering being consistent in the Figures and Table.

Quaternary (Figures 8 and 9). In some cases the rock formations studied contain beds of both Pliocene and Pleistocene age and for this reason it is convenient to include some Pliocene results here. In Europe and North America results are available from rock formations laid down in post-glacial and historic epochs. The directions of magnetization in 11 lava flows of Mt Etna covering a period of 2 305 years have been measured by Chevallier (1925) (pole **1**). Two sections of varved sediments spread over a period of 1 850 years have been studied by Griffiths (1955) samples being taken approximately every 20 years (**3**). Pole **4** has been obtained from the mean direction of 8 post-glacial lava flows (Hospers 1955) from Iceland covering a period of about 5 000 years, a result which has been recently confirmed by Brynjolfson (1957). A sequence of varves from New England covering a period of 6 000 years have been studied by Johnson & others (1948) (**10**).

Results from the Pleistocene and Late Pliocene have been reported from many parts of the world. Results from 8 lava flows in Central France which straddle the Plio-Pleistocene boundary have been recorded by Roche (1951) (**2**). Hospers (1955) has given results from the Early Quaternary lava flows of Iceland (**5**). This work has been extended by Sigurgeirsson (1957) who has also studied Pliocene lava flows. Sigurgeirsson considers flows with negative and positive magnetization separately (**6** and **7**) and does not distinguish between Pleistocene and Pliocene flows. In Japan nine volcanic groups have been studied from Central Honshu

Table 1

Pole positions obtained from palaeomagnetism. Northern hemisphere polar co-ordinates are given; $d\psi$ and $d\chi$ are the semi-axes of the elliptical error area round the pole at a probability of 95 per cent, $d\psi$ in the colatitude direction and $d\chi$ perpendicular to it. Other symbols are explained in section 4.

	Country	Rock Units	Age	Sign	Pole Positions				
					No.	Lat. N	Long.	$d\psi$	$d\chi$
Quaternary	Italy	Lava flows of Mt. Etna	394 BC to 1911 AD	−	•1	86·3	125·5E	7·3	9·9
	France	Lava flows of Central France	Villafranchian and Pleistocene	+	2	77·9	93·3E	15·7	20·3
	Sweden	Varved sediments of the Angerman River	1100 BC to 750 AD	−	•3	88·4	160·2E	12·0	13·0
	Iceland	Post glacial lava flows of S.W. Iceland	Approximately 5000 BC to 0 AD	−	•4	86·0	151·9E	13·3	14·8
		Lava flows of W. and S.W. Iceland	Early Pleistocene	+	•5	87·6	146·8E	11·5	12·6
		Normal lava flows	Pliocene and Pleistocene	−	6	87·8	149·0E	6·7	6·7
		Reversed lava flows		+	7	77·3	73·9E	6·7	6·7
	Japan	North Izu and Hakone volcanic regions	Lower Pleistocene through to Holocene	+ & −	•8	76·4	37·6E	7·1	10·4
		Kawajiri basalt	Early Pleistocene	+	•9	80	49E	—	—
	U.S.A.	Varves of New England	13000 BC to 7000 BC	−	•10	80·5	131·8E	9·5	13·6
	Argentina	Lava flows	Quaternary	+ & −	11	83	126E	6	7
	Australia	Newer Volcanics of Victoria	Pliocene, Pleistocene and recent	+ & −	12	86·3	77·9W	5·5	7·2
Neogene	France	Lavas of Mt Dore and the Limagne	Pontian and Pliacentian	+	•13	73·1	167·3W	13·6	19·2
	Iceland	Lavas of the north and north-west	Miocene	+ & −	•14	88·6	5·2E	9·6	10·3
	U.S.A.	Columbia River basalts	Miocene and Pliocene	+ & −	•15	87	40E	4·5	3·6
	New Zealand	Ignimbrites of the North Island	Pliocene	—	•16	79·2	35·2E	?	?

Palaeogene and Cretaceous	Scotland	Mull lavas	Lower Tertiary, probably Eocene	+	•17	82	71W	28	31
		Mull Intrusives	Lower Tertiary	+ & −	•18	72	139E	11	14
		Dykes of Arran		+ & −	•19	79	154E	12	15
	England	N.W. dykes of Northern England	Oligocene	+	•20	86	76W	21	25
	Ireland	Lower basalts of Antrim	Lower Tertiary, probably Eocene	+	•21	74	133E	6	8
	France	Intrusive basalt of the Limagne	Aquitainian	+	•22	77	3E	—	—
		Sills and dykes of Gergovie		+	•23	73	119E	12	16
	India (Deccan Traps)	Lavas from Bombay State	Late Cretaceous to Eocene	+ & −	24	28	78W	10	15
		Linga area, lavas near base of the sequence		+	25	37	83W	13	19
		Khandala area, upper part of middle of sequence		+	26	25	79W	14	18
		Kambatki ghat		+	•27	31	103W	—	—
		Igatpuri ghat		+	•28	36	87W	—	—
		Nipani area, lower flows		+	29	35	95W	—	—
		Nipani area, upper flows		−	30	52	70W	3	5
		Amba ghat, lower flows		+	31	27	76W	8	10
		Amba ghat, upper flows		−	32	52	64W	—	—
		Mt Pavagadh, lower flows		−	33	58	91W	4	8
		Mt Pavagadh area, upper tuffs	Lower Tertiary	−	34	75	89W	—	—
	U.S.A.	Siletz volcanics	Lower and early middle Eocene	+ & −	35	37	50W	7	10
		Laney shale, Wyoming	Eocene	−	•36	86	164W	8	10
	Australia	Older Volcanics of Victoria	Lower Tertiary, probably Eocene	+ & −	37	66·8	57·3W	10·8	12·1
	U.S.A.	Dakota Sst.	Cretaceous	+	38	77	127E	9	11
Jurassic	Scotland	Lsts. and ssts. from Skye and Brora	Jurassic	+ & −	39	56	76E	—	—
	India	Rahajmahal traps	Jurassic	−	40	13	70W	7	8
	Rhodesia	Karroo basalt	Jurassic	−	41	60	77W	4	6
	South Africa	Karroo dolerites (surface samples)	Jurassic	+ & −	42	76	128W	14	19
		Karroo dolerites and baked sediments (Underground samples)	Jurassic	+ & −	•43	69	93W	13	13
	Brazil	Serra Geral lavas and baked Botacatu sst.	Jurassic	+ & −	44	83	126W	2	3
	Australia	Tasmanian dolerites	Jurassic	+ & −	45	50	23W	7	7

Table 1—*continued*

	Country	Rock Units	Age	Sign	Pole Positions No.	Lat. N	Long.	$d\psi$	dx
Triassic	England	New Red Sandstone	Triassic	+ & −	*46	43	131E	7	12
	France	Red sst. of the Vosges	Triassic	+	*47	28	143E	6	12
	U.S.A.	Lavas and sediments Connecticut valley	Upper Triassic	+ & −	48	55	88E	8	15
		Lavas Connecticut valley	Upper Triassic	−	49	54	90E	6	11
		Brunswickian formation of Newark Series	Upper Triassic	−	50	63	93E	3	6
		Springdale sst.	Upper Triassic	−	51	55	107E	—	—
	Bechuanaland	Kgoma Series	Upper Triassic	−	52	54	44W	5	10
	Australia	Brisbane tuff.	Triassic	+ & −	53	39	37W	—	—
Permian	Scotland	Mauchline lavas	Permian, most likely belong to the lower Permian	+	54	36	175E	3	8
		Mauchline sediments	Permian, most likely belong to the lower Permian	+	55	37	163E	6	12
	England	Exeter Traps	Permian, most likely belong to the lower Permian	+	56	43	164E	10	20
	France	Esterel lavas (flow R3)	Permian, most likely belong to the lower Permian	+	57	45	131E	—	—
		Esterel lavas (flow R4)	Permian, most likely belong to the lower Permian	+	*58	46	141E	—	—
		Esterel dolerite	Permian, most likely belong to the lower Permian	+	*59	53	165W	—	—
		Nideck porphyry	Permian (Saxonian?)	+	60	43	168E	2	5
		Montcenis sst.	Saxonian	+	61	38	162E	—	—
	Norway	Lavas of Oslo graben	Permian	+	62	46	165E	7	11
	Germany	St. Wendel sst.	Permian	+	63	45	175W	—	—
	U.S.A.	Supai beds (Runcorn)	Lower Permian	+	64	26	121E	6	8
		Supai beds (Doell)	Lower Permian	+	65	39	115E	4	7
		Supai beds (Graham)	Lower Permian	+	*66	41	117E	—	—
	Kenya	Majiya Chumvi	Upper Permian	+	67	4	150E	—	—
	Kenya	Taru grit	Lower Permian	?	68	0	87E	—	—
	Australia	Lower Marine Series	Lower Permian	+	69	38	6W	—	—
		Upper Marine Series	Middle Permian	+	70	27	11W	21	21

Carboniferous	England	Pennant sst.	Upper Carboniferous	−	*71	43	114E	—	—	
		Clee Hills sills and contact rocks		+	*72	27	155E	?	?	
		Tideswelldale baked rocks		+	*73	5	143E	?	?	
		Lundy Granite		+	*74	43	180E	—	—	
	U.S.A.	Naco Sst.		+	75	41	120E	4	8	
	Australia	Kuttung (sediments)		+ & −	76	32	15W	12	12	
		Kuttung (lavas)		−	77	43	30W	16	16	
	England	Toadstones		−	78	55	148E	11	17	
	Scotland	Kinghorn flows (41–46)	Lower Carboniferous	−	*79	8	153E	?	?	
		Kinghorn flows (48–54)		+	*80	12	158E	?	?	
		Kinghorn flows (64–65)		−	*81	42	150E	—	—	
	U.S.A.	Barnett formation (normal)		−	82	42	142E	—	—	
		Barnett (reversed)		+	83	41	128E	?	?	
	England	Shatterford intrusion	Carboniferous undifferentiated	+ & −	*84	32	137E	—	—	
		Sediments from the northern counties		−	*85	51	143E	?	?	
Devonian	Britain	Old Red Sandstone	Lower and Upper Devonian	+	86	30	159E	3	5	
		Brownstones	Lower Devonian	+	87	25	102E	—	—	
	Australia	Ainslie volcanics	Lower Devonian?	−	88	66	168W	7	13	
Silurian	U.S.A.	Clinton iron ore	Middle Silurian	+	89	35	138E	—	—	
		Rosehill fm.	Middle Silurian	−	*90	19	138E	4	6	
	Australia	Mugga porphyry	Upper Silurian	−	91	60	157W	—	—	
Cambrian	Wales	Caerbwby sst.	Lower Cambrian	+	92	15	173E	8	10	
	U.S.A.	Wilberns fm., Point Peak member	Cambrian	?	93	0	158E	—	—	
	Australia	Elder sst.	Middle Cambrian	+	94	34	172W	5	10	
		Antrim plateau basalts	Lower Cambrian, possibly uppermost Proterozoic	+ & −	95	36	154W	6	12	

Table 1—*continued*

Country	Rock Units	Age	Sign	Pole Positions				
				No.	Lat. N	Long.	$d\phi$	dx
England	Longmyndian	Upper Pre-Cambrian	+ & −	**96**	2	120W	7	13
Scotland	Upper Torridonian Sandstone Series	Upper Pre-Cambrian	+ & −	**97**	6	43E	4	6
	Lower Torridonian Sandstone Series	Upper Pre-Cambrian	−	**98**	35	118W	5	8
U.S.A.	Portage Lake Group, lavas	Middle Keweenawan	−	**99**	25	170W	5	7
	Copper Harbour Group, red sst. and lavas	Upper Keweenawan	−	**100**	30	176E	5	8
	Freda and Nonesuch Group, red sst. and shl.	Upper Keweenawan	−	**101**	9	169E	2	3
	Jacobsville Group, red sst.	Upper Keweenawan	−	**102**	14	10E	7	13
	Chequamegon Group, sandstones	Upper Keweenawan	−	**103**	69	47W	10	11
	Michigan diabase dykes	Upper Pre-Cambrian	+	**104**	45	99W	2	2
	Hakatai shales (Runcorn)	Upper Pre-Cambrian	−	**105**	31	150W	9	10
	Hakatai shales (Doell).	Upper Pre-Cambrian	−	**106**	18	144W	27	30
	Hazel fm., flat lying red beds	Pre-Cambrian	−	**107**	49	175W	?	?
	Hazel fm., folded red beds	Pre-Cambrian	−	**108**	60	151E	?	?
Africa	Pilansberg dykes	$1290 \pm 180 \times 10^6$ years	−	**109**	8	43E	?	?
Australia	Buldiva Quartzite	Upper Pre-Cambrian	+	**110**	30	121W	8	14
	Nullagine lavas	Upper Pre-Cambrian	+	**111**	51	18W	10	13
	Edith River Volcanics	Upper Pre-Cambrian	+	**112**	6	14W	15	24

(Nagata & others 1957) and pole **8** has been obtained from an average of results from all these groups. The mean direction in one flow from western Honshu has been reported by Asami (1954) and pole **9** calculated from this is in good agreement with the results from Central Honshu. Much detailed work on sediments in Japan has been done but numerical values are not given and pole positions cannot be determined. In the southern hemisphere results are available from some Quaternary volcanics in Central Argentina (Creer 1958) (**11**) and from the Newer Volcanics of the western district of Victoria (**12**) (Irving & Green 1957). Thirty-two sites have been sampled at the latter which are for the most part of Pleistocene age although some of the younger flows are Recent and some of the oldest flows may be Pliocene.

All the post-glacial poles (Figure 8), and, with two exceptions, all the Plio-Pleistocene poles (Figure 9) coincide within their errors with the geographic pole.

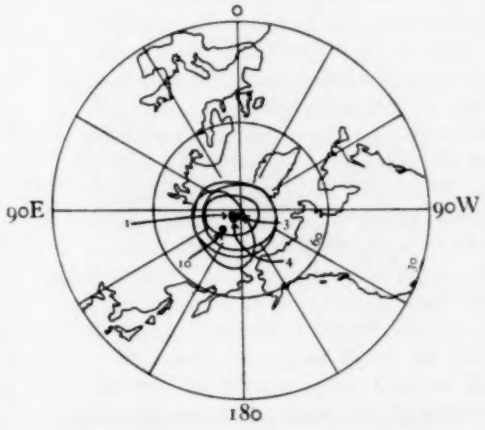

FIG. 8.—*Pole positions for post-glacial times.* The poles may be identified by referring to the Table.

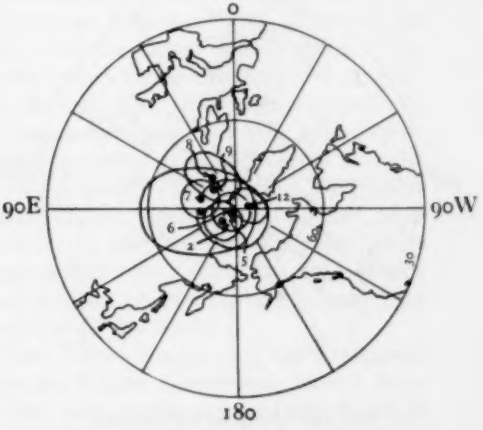

FIG. 9.—*Pole positions for Pleistocene and Plio-Pleistocene times.*

The divergence in pole **7** derived from the Plio-Pleistocene flows of Iceland is curious since these flows which have positive polarity are interbedded with flows with negative polarity whose directions of magnetization average to the dipole field (**6**). Secondary components of magnetization could be responsible but care has been taken to eliminate these by "washing" the specimens in alternating fields (Sigurgeirsson 1957). Since the sample size is fairly small (29 specimens) this result needs confirmation or rejection by further measurements. In Japan the declinations are consistently westerly and in view of the large number of specimens measured spanning the period from early Pleistocene to Holocene this divergence is probably significant. It could be explained by an anti-clockwise rotation of Japan by $16° \pm 8°$ during the past million years.

Neogene. (Figure 10). Roche (1951) has obtained the directions of magnetization from 2 lava flows of Upper Miocene and 3 of Lower Pliocene age (pole **13**). Hospers (1954) sampled over 100 flows in the Neogene plateau basalts of Iceland (**14**). Seventy-three flows in the Columbia River basalts have been sampled by

Campbell & Runcorn (1956) (**15**). Pole **16** is from the ignimbrites of New Zealand (Hatherton 1953). Poles for the Iceland lavas and the Columbia River basalts which are the most thoroughly sampled formations coincide, within the errors, with the geographic pole. The small divergence of the French pole (3° at the 95 per cent confidence limits) could be due to the comparatively small number of flows sampled.

Palaeogene and Cretaceous (Figure 11). The lava flows of Mull and certain dykes have scattered directions of magnetization in some cases random (Bruckshaw & Vincenz 1954, Vincenz 1954). Directions in 8 flows and 5 dykes are not random and poles **17** and **18** have been calculated from these. The dykes of Arran and their contact sediments (Leng 1955, 10 sites) and the north-west trending dykes of

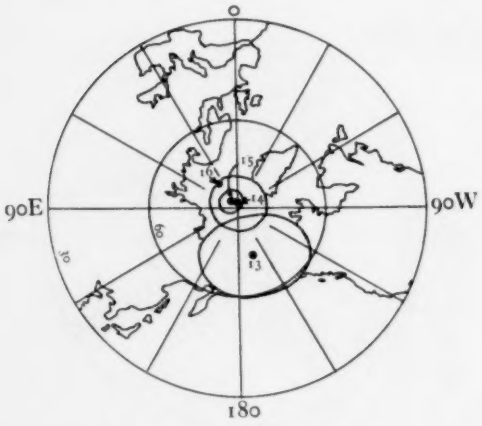

FIG. 10.—*Neogene pole positions.*

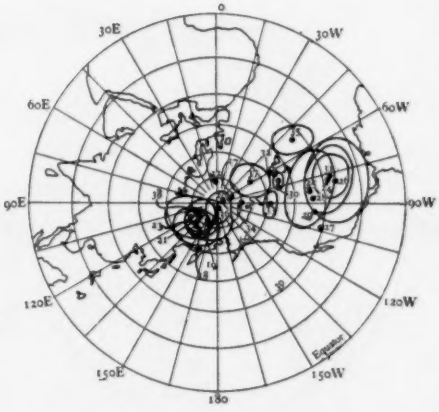

FIG. 11.—*Palaeogene and Cretaceous pole positions.*

northern England (Bruckshaw & Robertson 1949, 7 sites), which are representative of the last phase of Tertiary igneous activity in Britain, give the poles **19** and **20**. Twenty-four flows from the Lower Basalts of Northern Ireland have been sampled by Hospers & Charlesworth (1954) (**21**). The directions of magnetization of the intrusives in the Limagne and Gergovie (**22**, **23**) have been surveyed by Roche (1950 a and b, see Hospers 1955). The Mull lavas and N.W. dykes of England have very large associated errors which are not plotted on Figure 11 to avoid confusion. The other European poles are better defined and there is a tendency to occupy easterly longitudes in latitudes between 70 and 80°.

Many results are available from the Deccan Traps of India (Irving 1956a, Clegg & others 1956, 1957, Deutsch & others 1958). The traps are of uppermost Cretaceous or Eocene age with the possibility that some of the highest levels may be as young as Oligocene (discussion in Krishnan 1949). Samples have been taken from many places but unfortunately the stratigraphic relation of these localities to one another is generally not known. Samples at 9 sites in the Linga area (**25**), 20 sites covering 2050 feet in the Khandala area (**26**), 5 sites spaced through 1300 feet in the lower part of Amba Ghat (**31**), 7 sites in Bombay State (**24**), 3 lava flows at Igatpuri Ghat (**28**), a single flow at Kambatki Ghat (**27**), and one

flow in the Nipani area (**29**) give pole positions in the region of the southern United States. This represents good agreement from many determinations. Results (**32**, **30**) from the upper flows at Amba (25 feet) and at Nipani (5 sites), from the lower flows (8 flows pole **33**) and upper tuffs (2 sites pole **34**) at Mt Pavagadh give poles in similar longitude but more northerly latitudes. The former groups have positive polarization whereas the latter are all negative. The differing latitudes of the poles could therefore be due to secondary I.R.M. However, at any one locality the upper sections always give poles nearer to the geographic pole than lower sections and could be due to polar wandering during the time the Traps were being laid down. An alternative proposal is that differing depths of burial have produced these differences.

Apart from work by Cox (1957) (**35**) on the Siletz volcanics of Oregon few results are available from the Palaeogene of North America. Early work by Torreson & others (1949) on Tertiary sediments in the Western United States suffered from a lack of adequate stability evidence (Hospers 1955). However, for comparison with Cox's work a result (**36**) from the Laney shale is given. This pole coincides with the present geographic pole whereas Cox's pole is in mid-Atlantic. Cox has studied 8 flows spread through about 4000 feet, and reversals occur. It is somewhat unlikely therefore that its divergence from the present pole is due to failure to average out the secular variation. It is noteworthy that the distance of pole **35** from Oregon, $55° \pm 7$, is not greatly different from the present co-latitude of 45° and the large observed divergence could, in part at least, have resulted from a clockwise rotation of this particular part of Oregon since the middle Eocene. The region has undergone orogenic movement since that time so this possibility has to be borne in mind. Measurements on undisturbed Eocene rocks from other regions of North America should settle the matter.

Runcorn (1955) has given the pole from North America for the Cretaceous Dakota Sandstones (**38**). Certain Turonian (Upper Cretaceous basalts from Madagascar have directions of magnetization close to the present field (Roche & others 1958) and could possess a secondary magnetization. Pole **37** has been obtained from samples from 15 sites in the Older Volcanics of Victoria, Australia (Irving & Green 1957).

Jurassic (Figure 12). Clegg & others (1958) have given a result (**40**) from the Rahajmahal traps of India. Eight lava flows from Bulawayo and the Victoria Falls sampled by Nairn (1956) give pole **41**. In the Union of South Africa samples have been collected (Graham & Hales 1957) from 20 sills and dykes (pole **42**) at surface exposures, and from sills and associated baked sediments in two mines. The underground samples are from 2 sills at Winkelhaak in the Transvaal and 2 sills and baked sediments at Estcourt in Natal and pole **43** has been calculated from a mean of these, thereby probably eliminating secular variation. Creer (1958) has given the pole (**44**) for the Serra Geral volcanics and associated sediments in Southern Brazil, and Irving (1956b) the pole **45** from 30 sites in the Tasmanian dolerites. The formations referred to above are usually regarded as Jurassic, but in some cases, for instance, the Tasmanian dolerites, the possibility of a Cretaceous age although much less probable cannot be excluded. From the northern hemisphere there is only one preliminary result (**39**) obtained from various sedimentary rocks in Scotland (Nairn 1957b).

Triassic (Figure 13). Clegg & others (1954, 1957) have obtained results from the Triassic of England and France, nine sites in each case (poles **46**, **47**). There are

four determinations (**48**, **49**, **50**, **51**) from the Upper Triassic of the United States (Du Bois & others 1957). The determinations from South Africa (**52**) and Australia (**53**) have been given by Nairn (1957a) and Irving & Green (1958).

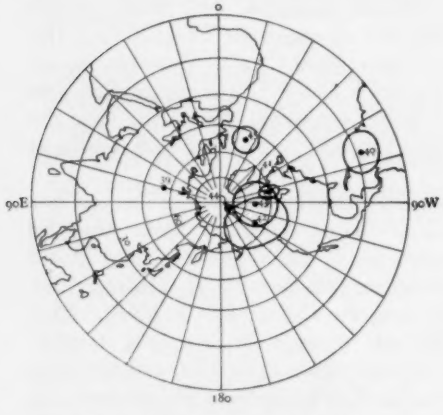

FIG. 12.—*Jurassic pole positions.*

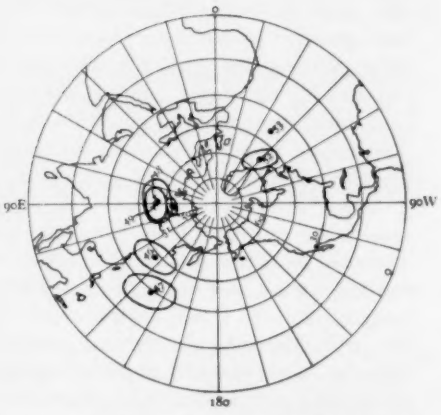

FIG. 13.—*Triassic pole positions.*

Permian (Figure 14). Results from samples spaced through 500 feet of basalt at Mauchline in Scotland give pole **54**, and **55** is obtained from sampling through 2 100 feet of the overlying red sandstones (Du Bois, 1957). Pole **56** has been obtained by Creer (1957a) from 5 lava flows in Devonshire. Determinations from two flows and one dolerite in the Esterel lavas of Central France (Roche 1957,

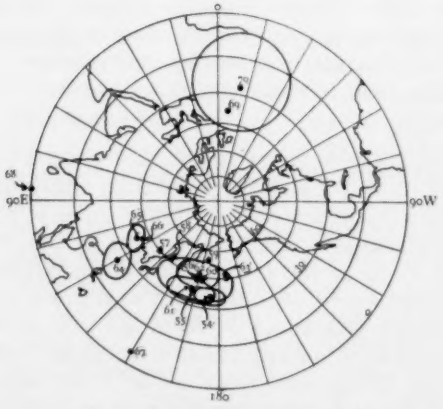

FIG. 14.—*Permian pole positions.*

Rutten & others 1957) give poles **57**, **58** and **59**. The porphyries of Nideck, the red sandstones of St Wendel in Saarfalz, and the red sandstones of Montcenis have provided poles **60**, **63** and **61** (Nairn 1958). Rutten & others (1957) have obtained results from 15 lava flows near Oslo (**62**). There are three independent determinations (**64**, **65**, **66**) from the Supai beds in Arizona (Runcorn 1955, Doell 1955, Graham 1955). Poles have also been given by Nairn from Kenya (**67**, **68**) (Creer

& others 1958), and from Australia there are two results (Irving & Green 1958), **69** and **70**, the former being based on the one lava flow from the Hunter River Valley and the latter from 3 flows from the Illawara coast.

Carboniferous (Figure 15). Carboniferous rocks in Britain have been extensively studied. Results from a single site in the Pennant sandstone (**71**) have been reported by Clegg & others (1954). Clegg & others (1957) have given results from

FIG. 15.—*Carboniferous pole positions.*

igneous rocks and associated baked sediments at Clee Hill (6 sites pole **72**), Tideswelldale and Shatterford (2 sites). They have also studied 3 groups of 5, 6, and 2 lava flows from Kinghorn (**79**, **80**, **81**). Belshé (1957) has given results from igneous and sedimentary rocks (**78**, **85**). A result by Blundell (1957) from Armorican granites of Lundy Island gives pole **74**. The poles from Britain are scattered widely over the north-eastern Pacific, but unfortunately the errors in this work have not always been published and in many cases (**71**, **81**, **84**) limited thicknesses have been sampled so that it is impossible to assess the errors due to experiment and secular variation. Runcorn (1955) has sampled from 200 feet of Naco sandstone (**75**). Howell & Martinez (1957) have sampled from one site (**82**) and 8 sites (**83**), from the Barnett formation. From Australia there are results from sedimentary (**76**) and igneous rocks (**77**) in the Kuttung Series of the Hunter Valley.

Devonian (Figure 16). Creer (1957a) has given results from 35 sites in the Lower and Upper Old Red Sandstone of the Welsh cuvette (**86**). Results from one locality in the Brownstones (Clegg & others 1954) give pole **87**. Results from igneous rocks at Mt Ainslie near Canberra give pole **88** (Irving & Green 1958); there is some uncertainty as to whether these beds are Silurian or Devonian.

Silurian (Figure 16). Seven samples from a limited vertical sequence in the Clinton iron ore gives pole **89** (Howell & others 1958). Samples from 5 sites in the somewhat older Rosehill formation (Graham 1949) give pole **90**. No results are available from the Ordovician. Pole **91** is from a porphyry intrusion near Canberra (Irving & Green 1958).

Cambrian (Figure 16). Cambrian results are available from the Caerbwby sandstone in Wales (**92**) (Creer 1957a), the Point Peak member of the Wilbern's formation (**93**) (Howell & Martinez 1957), and the Elder Mt sandstone and Antrim plateau basalts of Western Australia (**94**, **95**) (Irving & Green 1958).

Pre-Cambrian (Figure 17). Creer (1957a) has sampled 12 sites in the Longmyndian (**96**). Samples from 111 sites spaced through 11 000 feet of the Torridonian Sandstone yield pole **98** for the Diabaig and lowest beds of the Applecross group, and pole **97** for the remainder of the Applecross and Aultbea groups (Irving & Runcorn 1957). Du Bois (1957) has obtained 5 pole positions from successive levels in the Middle and Upper Keeweenawan; 31 lava specimens from the Portage lake group give pole **99**, 25 specimens from red sandstones and lavas in the Copper Harbour pole **100**, 68 specimens from red sediments in the Freda and Nonesuch

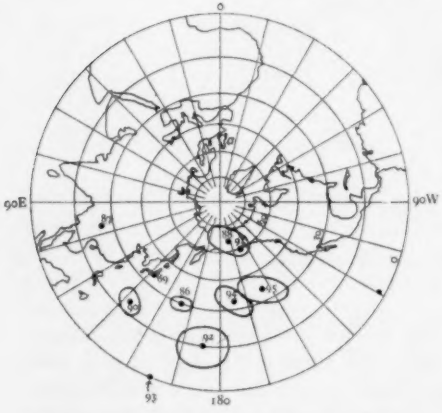

FIG. 16.—*Pole position for Cambrian, Silurian and Devonian.*

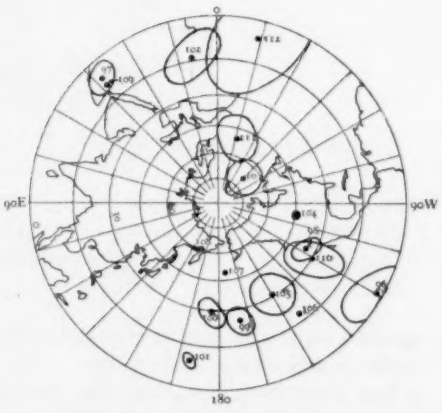

FIG. 17.—*Pre-Cambrian pole positions.*

group pole **101**, 15 specimens from the Jacobsville group pole **102**, and pole **103** has been obtained from 15 specimens in the Chequamegon group. Graham (1953) has measured the magnetization directions in 5 dykes from Baraba County, Michigan (**104**). Runcorn (1955) and Doell (1955) have given the pole for the Hakatai Shales of the Grand Canyon (**105**, **106**). Howell & Martinez (1957) have studied the red beds of the Hazel formation of west Texas and obtained pole **107** for flat-lying beds (5 sites) and **108** for folded beds (9 sites). The Pilansberg dykes measured by Gough (1956) (**109**) have recently been dated by isotope decay methods (Schreiner 1958). Three results, **110**, **111**, **112**, are available from Australia (Irving & Green 1958).

5. Discussion of results

For Devonian and earlier periods results are comparatively few, the time spans vast, and the results highly scattered. For Carboniferous and younger periods the results are numerous and the following remarks may be made about them.

(1) The results from the Neogene and Quaternary from different continents are in good agreement with the present geographic pole (Figures 8, 9 and 10). The

small divergences that do occur could be due to sampling inadequacies and small rotations of limited areas in tectonically active regions such as Japan. The Earth's field has remained predominantly an axial dipole.

(2) With a few exceptions (**36**, **44**) polar results from older rock formations diverge considerably from the present geographic pole. Polar results from Carboniferous and Permian rock formations are generally found to be in intermediate latitudes. Thereafter, in the Mesozoic and Palaeogene, they occupy higher latitudes.

(3) In *most* cases there is good but not always exact agreement between results from rock formations laid down in the *same* continent during the *same* geological period. The agreement between the ten results (**54** to **63**) from Permian beds in five European countries is most striking (Figure 14). Other examples are the Palaeogene of Europe (**18** to **23**, Figure 11), the lower sections of the Deccan Traps (**24** to **29** and **31**, Figure 11), the Jurassic of Africa (**41** to **43**, Figure 12), and the Triassic of the United States (**48** to **51**, Figure 13). Divergences do occur, for instance, pole **57**, obtained from measurements on a single lava flow from the Esterel, differs somewhat from the main group of determinations from the European Permian (Figure 14). However an adequate time average has not been achieved and the divergence is probably due to secular variation.

(4) The agreement referred to occurs between igneous and sedimentary rocks in a variety of geological environments.

(5) Polar results derived from rock formations laid down prior to the Neogene and in the *same* geological period but situated in *different* continents in general do not agree with one another.

(6) Positive and negative polarizations are found in all periods except in the Permian, in which only positive polarizations have so far been recorded, and in the Ordovician, for which there are no results.

(7) The polar results from various formations in the Carboniferous of the United Kingdom show wide scatter (Figure 15).

6. Comparison of results within and between continents

Of the points listed above the contrast in Permian to Palaeogene times of agreement between results from the *same* continent and disagreement between results from *different* continents is of first importance. The remainder of this review is devoted to a discussion of this matter. An informative procedure for comparing results within and between continents is to plot frequency histograms of the separation of poles taken two at a time first from the same and then from different continents. Poles must be used from the same unit of geological time, the unit being chosen sufficiently long to allow correlation of the unit as a whole from continent to continent, that is, a geological period for the time considered. For the internal comparison if n poles have been calculated from such a time unit within one continent there are $\frac{1}{2}n(n-1)$ pole pairs. For the external comparison, if $n_1, n_2, \ldots, n_m$ poles are known from m continents, the number of pole pairs is $\frac{1}{2}\{(\Sigma n)^2 - \Sigma n^2\}$. In the first case an estimate is obtained of the amount of polar wandering as viewed from one continent during a known period of geological time. This should agree with the external comparison if polar wandering *only* has occurred.

This analysis has been done for seven time intervals all of approximately equal duration. They are the Quaternary and Neogene approximately 28 million years, the Palaeogene 32 million years, Jurassic 25 million years, Triassic 30 million

years, Permian 25 million years, the Upper Carboniferous 25 million years and Lower Carboniferous 30 million years. All the results from the Deccan Traps are included in the analysis for the Palaeogene although this formation may extend down into the uppermost Cretaceous. The results for the Quarternary and Neogene are given in Figure 18. Both internal and external agreement is good, the divergences commonly ranging up to 20°. The Permian results, which are typical of the earlier periods, are plotted in Figure 19 and the results for the Permian, Triassic, Jurassic and Palaeogene combined in Figure 20. The divergence between pairs of poles within each time unit from a single continent range up to 30° with very few higher values. This is about 10° more than the range for the

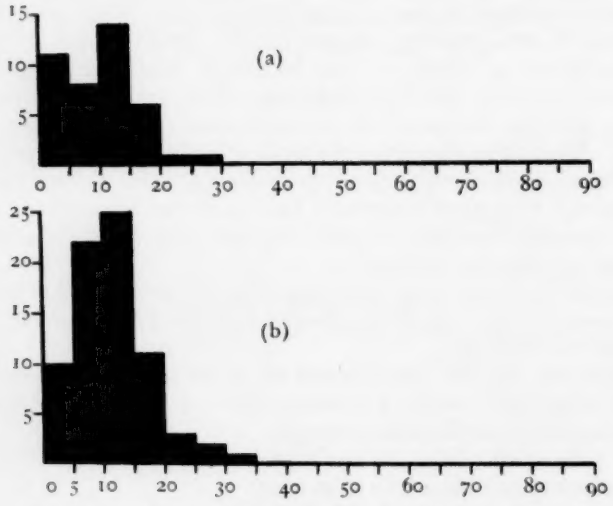

FIG. 18.—*Variation in the Quaternary and Neogene.* The height of each column in the histograms in Figures 18 to 21 represents the number of occurrences of divergences of pole pairs in the ranges indicated on the horizontal axis.

(a) within continents (b) between continents.

Quaternary and Neogene. The sampling from the latter is concentrated in the Quaternary (12 poles) with fewer determinations (4 poles) for the Neogene which represents a much longer period. Thus, the range shown in Figure 18 may be too small, and 30° could represent a more accurate range of polar wandering during periods of approximately 20 to 40 million years. In contrast, the pairs for different continents have separations commonly ranging between 35° and 90° and rarely approach closer than 20°.

In the Carboniferous the scatter of poles in the European results is greater than that for other epochs. The Carboniferous period lasted for approximately 55 million years, or about twice as long as the younger units, and for this reason the results are divided into Upper and Lower groups corresponding approximately to the Pennsylvanian and Mississippian (25 and 30 million years). The external divergences (Figure 21) are again greater than the internal although the latter are more scattered than in later periods. Thus, it seems that in the Carboniferous polar movement may have been greater than that in subsequent periods. The

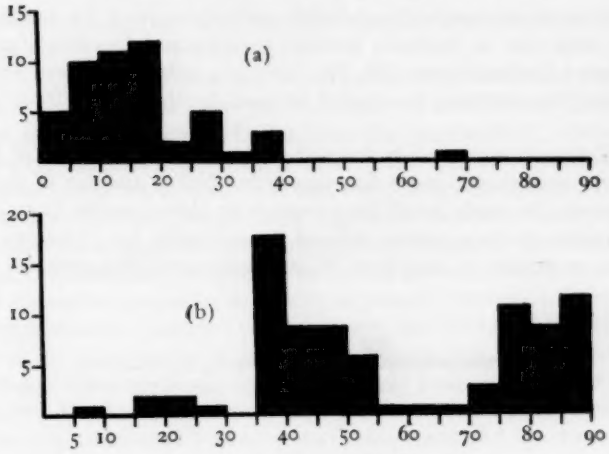

FIG. 19.—*Variation in the Permian.*
(a) within continents (b) between continents.

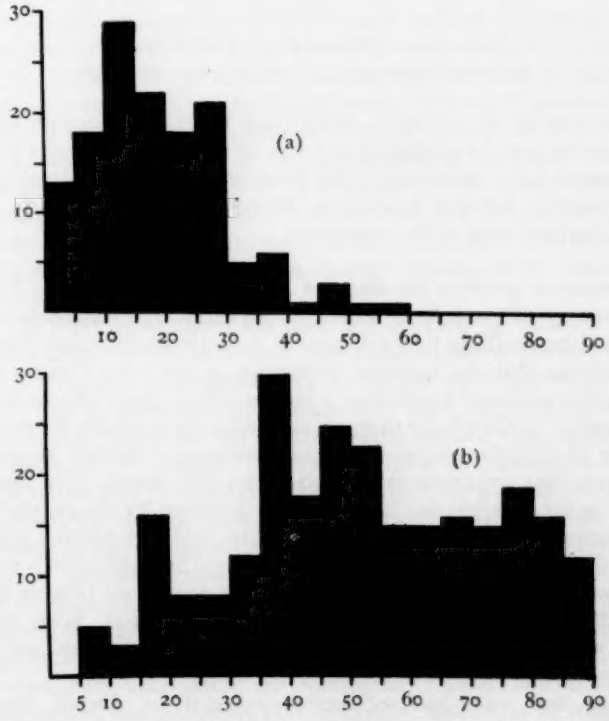

FIG. 20.—*Combined results from the Permian, Triassic, Jurassic and Palaeogene.*
(a) within continents (b) between continents.

results are not numerous and a reliable estimate cannot be made. It is interesting to note that in Australia between Silurian and Devonian (poles **91** and **88**) and Upper Carboniferous (**76**, **77**) there is a polar change not less than 60° of arc accomplished during the period covered by the results from the United Kingdom.

In pre-Carboniferous periods the picture is less clear because of the limited sampling over very much longer time intervals. Before analysis of the type described above can be made it will be necessary to obtain results from each epoch within each period, since epochs defined by geologists for Devonian and older systems are comparable in length to Mississippian and later periods.

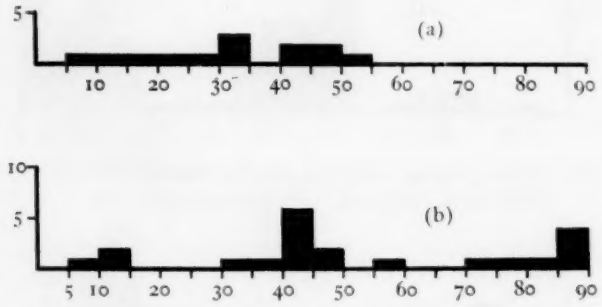

FIG. 21.—*Variation in the Carboniferous*
(a) within continents (b) between continents.

This contrast in the variation within and between continents illustrated in Figures 18 to 20 may be explained in terms of the failure of rocks to "fossilize" the geomagnetic field, variations in the behaviour of the field, inadequate stratigraphic correlation between continents, tectonic movements within continents, or relative displacements of the continents.

Failure of rocks to preserve the direction of the geomagnetic field. Elongated or discoid ferromagnetic particles in sediments are likely to be magnetized along their longer axes. Upon settling they will tend to lie horizontally rather than along the magnetic field so that the resultant inclination is too low. Compaction during lithification of a sediment could have a similar effect. Such effects do not apply to igneous rocks, or chemically magnetized sediments in which the ferromagnetic particles are of irregular shape. In rocks possessing a detrital magnetization it seems unlikely that important errors arise from this source. For instance, it is not present in the Torridonian Sandstone, as is shown by the parallel directions of magnetization in slumps and enclosing undisturbed beds (Irving 1957). Also, in varved sediments, which are the other rocks whose magnetization is attributed to detrital grains, the mean direction is parallel to the dipole field (Figure 8, **3** and **10**) and the inclination error observed (Johnson & others 1948, King 1955) in redeposition experiments in the laboratory either did not occur during deposition under natural condition or has been corrected since.

In aeolian and water-laid sediments elongated or discoid ferromagnetic particles magnetized along their long axis could have their alignment affected by wind or water currents. No aeolian beds have yet been studied so such an effect is relevant only to water-laid sediments possessing a detrital magnetization. The

agreement between igneous and sedimentary rocks discounts the effect. A detailed discussion has been given by Irving (1957).

Secondary I.R.M. components are common and may obliterate the primary magnetization. In the results from pre-Miocene rocks considered here this has not happened since the directions lie far from the present field. However, less obvious secondary components may be present so that the observed directions lie in the plane containing the present field and the primary component (Figure 7). In rock formations containing positive and negative polarizations in approximately equal proportions the average direction irrespective of sign is that of the primary magnetization, the secondary component being lost so that the effect only applies to those rock formation in which one polarity is present or in which the two polarities are disproportionate. Runcorn (1956a) shows that the effect is to change the *latitude* only of the calculated pole; in rock formations with negative polarization the calculated pole is too northerly, and in the case of positive polarization the pole is too far south. For instance, the Triassic sandstones of France have positive polarization somewhat affected by a secondary component of magnetization (Clegg & others 1957). The pole is to the south of, but in the same longitude as, the pole calculated from the Triassic sandstones of England (Clegg & others 1954) which have both positive and negative polarities. Secondary components cannot, however, account for the wide longitudinal spread of polar results.

The argument that palaeomagnetic results allow the behaviour of the Earth's field in the remote geological past to be determined has met with much criticism because of the possibility that the stress history of rocks could cause permanent deflections of the primary magnetization (Graham 1956, Graham & others 1957). Two situations are envisaged in which this may occur: (1) in both igneous and sedimentary rocks as a result of stresses operative during tectonic activity, and (2) in igneous rocks which acquire a T.R.M. in the direction of the Earth's field under stresses which are subsequently relieved. For example, hyperbyssal rocks become magnetized under non-hydrostatic load, and in these and in lava flows, cooling stresses may be operative at the time the T.R.M. is acquired. Relaxation occurs by jointing, by removal of the overburden through erosion, or by removal of the specimen from the outcrop.

Evidence for the first of these has been put forward by Graham & others (1957) who have shown in the laboratory that linear compressions of 250 kg/cm^2 can change the directions of magnetization in certain metamorphic rocks by as much as 30°. This is presumptive evidence only since the deflections are not permanent; with few exceptions the magnetizations resume their original orientations after the stress is released. In any case the material used is irrelevant. The specimens tested are Pre-Cambrian gneisses which are not useful for geomagnetic investigations for obvious reasons. In the experiments deflections occurred only in magnetite or ilmenomagnetite-bearing gneisses whereas the directions of magnetization in gneisses containing haematite as their chief ferromagnetic constituent were little affected; in nature the agreement between lavas containing magnetite and red haematitic sediments of comparable age is good (poles **54** to **63** poles **48** to **51**, pole **100**) and such magnetostrictive differences are not apparent. Also, where secondary components are unimportant, folded and unfolded beds from the same period and continent have consistent directions of magnetization and compressive forces sufficient in some cases to produce vertical tilt have not affected the directions of magnetization (Graham 1949, Irving 1957).

The second case is rendered most improbable by the good agreement observed

between the directions of magnetization in igneous and sedimentary rocks of the same geological age (see above), and by the laboratory experiments of Stott and Stacey (1959). They have shown that the directions of T.R.M. acquired by igneous rocks under directed pressure of 500 kg/cm^2 which is later released is parallel to the Earth's field in the laboratory and to the direction in duplicate specimens magnetized without stress. The specimens used are relevant material from lava flows and sills in Australia from which inferences regarding the direction of the ancient Earth's field have already been made. It has to be remembered however, that magnetic minerals often have their properties altered by heat treatment, and the properties of rock specimens after heating above the Curie point are not necessarily identical with those possessed by the rock initially. The extrapolation of results from heating experiments to actual situations in nature is not always a very certain matter.

Nevertheless, assuming magnetostrictive effects to be important in controlling the direction of magnetization of rocks it may be proposed that the Earth's elementary dipole has not changed its attitude throughout geological time and the observed polar successions are the result of varying stress histories. These would need to have been constant over continental areas but radically different in each continent for given periods of time. There is no geological basis for such a contention especially since the rock formations studied have been chosen because of their unaltered character and the absence of dynamic metamorphism. Such stress effects if present are likely to be too subtle to be detected geologically. A relevant test of such a hypothesis is to consider the consistency between results for a given period from a variety of geological environments in the same continent. If the range of stress histories found in these environments have important effects the results should not agree. There are uniform results from the Triassic of America (Du Bois & others, 1957, Figure 13) and the Permian of Europe (Figure 14), both including sediments and igneous rocks, some folded and others horizontal. Vertical magnetizations (that is directions perpendicular to the bedding) are found in a wide range of geological environments in Australia; Mesozoic dolerite intrusives magnetized under load (**45**), flat lying Permian lavas (**70**), and folded Carboniferous sediments and lavas (**76**, **77**). It is clear that there is no substantial basis in the observations available at present from either the field or laboratory for supposing that magnetostrictive effects are responsible for the contrast in the observed variation within and between continents.

Variations in the geomagnetic field. This contrast could result from variations in the behaviour of the field. There are two possibilities, either that the field has not remained a dipole field throughout geological time, or that it has remained a dipole field which, prior to Miocene times, underwent rapid oscillations of large amplitude, so that during the space of a geological period the pole traversed much of the Earth's surface. At first sight it would seem that the agreement between results for the same period from the same continent effectively discounts the latter. However, because of the possibilities of gross inadequacies in stratigraphic correlation and possible widespread thermal and chemical changes this is not necessarily so.

Inadequate stratigraphic correlation. In any continent the rock formations of a geological period represent only a proportion of the total time span of that period. In general, sections in different continents overlap, but the fractions of these which have received palaeomagnetic study probably do not, so that the record in different continents will deal with different fractions of time within each geological period.

If, say, within Permian times polar movements with amplitudes of 90° and periods of tens of millions of years occurred, the pole could appear to be approximately stationary in the time sample from one continent, whereas the longer time span covered by specimens from several continents could contain a wide scatter of poles, as is observed. Such polar oscillations must have decreased some time in the middle of the Tertiary, after which they became negligible (Figures 9 and 10). Now, for post-Carboniferous times, polar shifts between geological periods in the same continent are small. For instance, during the period from Upper Carboniferous to Jurassic the pole as measured from Australia has remained in the region of the Tasman Sea. Therefore the large polar oscillations postulated above must have followed approximately repeatable paths. Moreover they were in phase with the processes by which rocks became magnetized; that is, rock formations in successive geological periods in the same continent became magnetized when the pole was moving through similar sections of its cycle. These sections are different for different continents for the same geological period, being about 90° of arc away from one another in the case of Europe and Australia. Any such connection between polar oscillation and the matters referred to in section 2 seems unlikely. A further possibility is that the system boundaries are grossly diachronous. The observed difference of within- and between-continent variation could arise if the systems in different continents were out of step by twice or three times their length. This is geologically absurd for the Permian and later periods here considered.

Continent-wide heating and chemical effects. Let us suppose again a widely oscillating dipole field and that rocks become magnetized long after deposition by heating above the Curie temperature during burial, or, by chemical changes affecting the iron minerals. The contrast in the within and between continent variation could then be explained if these processes were in phase with the polar oscillations. This is unlikely, and in any case the chemical and heat treatment of the rock formation of the same geological period from different parts of the same continent would have to have been identical. The variety of structure within a continent makes this improbable. Furthermore heating above the Curie temperature for red sediments (Curie temperature 600 to 700°C) implies burial to 20 km or more which is not likely to have happened to the rock formations considered here. Lastly, such widespread chemical changes would almost certainly be visible petrologically. For instance, certain sandy dolomites from the Sawatch formation of Cambrian age from Colorado have directions of magnetization parallel to those observed in Carboniferous rocks from the same region (Howell & Martinez 1957). Petrological study suggests that these sediments were dolomitized long after deposition and this was accompanied by the partial replacement of glauconite by haematite, so that a magnetization appropriate to a later period is not surprising in this case. Substantial secondary chemical changes of this type are not apparent in the rock formations listed in the table which were chosen for study because of their unaltered character.

Tectonic movements within a continent. Relative rotations of regions within a continent would result in differing pole results, and the position of the Eocene pole (35) from Oregon could be explained in this way. The better agreement of poles within a continent compared with that between continents is evidence against the occurrence of such rotations, unless these have contrived to bring previously dispersed poles into agreement. It seems much more likely that tectonic rotations would increase dispersion.

The assumption of a geocentric dipole field. The disagreement of results from different continents could be evidence against the assumption of a geocentric dipole field. However, there are arguments in favour of such a field.

Continued westerly drift of the Earth's field at the present rate would result in an average dipole field in about 2 000 years. The westerly drift is attributed to the acceleration of the mantle relative to the core in which the field is generated. Thus, whatever the field in the core, it would appear on the surface as a dipole when averaged over periods of several thousands of years provided no substantial part of the field arises in the mantle (Creer & others 1957). This is consistent with data from lavas of Mt Etna and the Swedish varves which have been sampled for 2 305 and 1 850 years respectively and which average to the geocentric dipole field (Figure 8).

Further back in time the field as observed from four continents over the past million years has averaged to a dipole (Figure 9) and Neogene observations going back approximately 20 million years from Europe and North America give a similar result (Figure 10). Still further back in time, the internal consistency of results from the Triassic of the United States and the Permian of Europe indicate that for these periods of time the field has averaged to a dipole over areas of continental size. Moreover, it may be said with less precision, that the field for Permian and Triassic period as viewed from *both* Europe and North America has averaged approximately to a dipole as the poles all lie in the region of East Asia and the North Western Pacific. Statistical differences separate the poles from the two areas but the predominant component is dipolar.

Serial reversals of magnetization in Quaternary and Neogene rock formations indicate several reversals of the field during this time. These are thought to be intimately bound up with the average dipole nature of the field. Reversals of magnetization observed in rocks of greater age are not different in character (Irving & Runcorn 1957) and their occurrence is thus consistent with an average dipole field during previous periods.

Runcorn (1954) has argued that the Coriolis force dominates fluid motions in the core leading to the coupling of the geomagnetic dipole axis and the rotational axis. This is certainly true for the past 20 million years and if it has always been so the pole obtained from palaeomagnetism may be identified with the ancient geographic pole, which in turn may be checked against the palaeoclimatic evidence collected by geologists. It is found, in general, that rock formations containing evidence of hot climates have low magnetic inclinations whereas those supposed by geologists to have been deposited in cold climates have steep inclinations (Runcorn 1956b, Irving 1956a, Irving & Green 1958). This is consistent with an average dipole field parallel to the axis of rotation.

Thus, the hypothesis of an average dipole field is an extrapolation into remote geological time of the known behaviour of the field over the past 20 million years, and is analogous to the uniformitarian principles generally used in geology. Without this hypothesis the palaeomagnetic data imply that prior to the Miocene the field was not predominantly dipolar. This field was quite different from the non-dipole field nowadays since it remained approximately constant for periods of the order of 20–30 million years but underwent slow changes over periods of the order of hundreds of millions of years.

Relative continental displacement. The good agreement of poles within a continent but poor agreement between continents could mean that the continents behaving

as separate entities have moved relative to one another prior to the middle Tertiary. One possibility is that of an expanding earth with continents carried out along extending radii and no change in latitude or longitude. But this could not explain the variation between continents since the polar calculations are independent of the Earth's radius (Creer & others 1957). The second possibility is that of relative changes in longitude or rotations of the continents. Such movements can adequately explain the variation between continents. Attempts have been made to calculate these movements from the palaeomagnetic data (Du Bois 1957, Creer & others 1958, Irving 1958) and will not be repeated here. These are found to be broadly consistent with the continental displacements already suggested by Wegener (1924), Du Toit (1937), Carey (1955) and King (1953) on the basis of morphological, geological and biological evidence. The movements are predominantly longitudinal because the differences between poles for the same period for different continents are predominantly longitudinal, and are of the order of 10 000 km.

7. Concluding remarks

The study of rock magnetism is in its infancy, and is perhaps at about the same stage as palaeontology a century or more ago. Palaeontology progressed by systematic studies of faunas and floras, and in a similar way rock magnetism is likely, for the next decade at least, to benefit most from systematic descriptions of the magnetic properties of rock formations—their directions of magnetization, the stability of these directions studied by field and laboratory tests, and the properties of their ferromagnetic minerals. The reconnaissance stage of palaeomagnetism, when small numbers of specimens were taken from many rock formations, is closed, and detailed studies of single stratigraphic entities are required. The interpretation of palaeomagnetic data presents many difficulties and, in the words of Graham & others (1957) "the only obvious way of these is to have so many field observations from so many rocks of so many types in so many settings that the insidious influence of magnetostriction either taken alone or in conjunction with (other?) time dependent parameters is eliminated". It is gratifying to see that so much of this type of information is now coming to hand.

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Reports of Meetings

15th Meeting of the European Association of Exploration Geophysicists

The fifteenth Meeting of the European Association of Exploration Geophysicists was held in London in 1958, December.

Out of a total of twenty-one papers presented, three dealt with the International Geophysical Year, two with general theory and observations, seven described instruments and instrumental techniques and nine discussed case histories and interpretation methods.

The technical meeting was opened by Sir Vivian Fuchs whose remarks were followed by two papers on results of geophysical research in Antarctica. The first of these by *J. D. G. Pratt* dealt with the Transantarctic Expedition. Seismic shots were fired regularly every 30–85 km during the whole trip and gravity observations were made whenever the party stopped for meteorological observations. The seismic charges were placed in holes whenever possible, as an impression was gained that better results were obtained when charges were fired in proximity to solid ice, which was at an average depth of 70 m. The main uncertainty in gravity observations was due to altitude correction, as all altitudes were obtained barometrically. It was felt that when all I.G.Y. meteorological data have been reduced, a few stable periods could be selected for Antarctica, and from these barometric pressures could be interpolated allowing altitudes to be determined with an accuracy of $\pm$ 100 m., corresponding to uncertainties in free air gravity anomalies of $\pm$ 30 mgal. This unfortunately, is not good enough for geodetic purposes. Observation of sea tides on the ice shelf showed that while the short period waves are attenuated by pack ice quite quickly, long period waves and tides penetrate quite far. All the observations were made by means of a Worden gravimeter, with photographic recording, readings being integrated over a period of 10 min. Readings analysed so far have been satisfactory except that there is a difficulty with diurnal component. There is a strong diurnal component with a period of exactly 24 hours which is probably due to the operational technique adopted and which could not be eliminated easily. Some of the difficulties of work in Antarctica were illustrated by the fact that preparations for tidal observations took 95 days while actual observations were carried out for 57 days. Thus the most important requirements for successful research in Antarctica seem to be patience and persistence.

The second paper on Antarctica by *G. P. Woollard*, *E. C. Thiel* and *N. Ostenso* gave some preliminary results obtained on traverses from Little America and Marie Byrd Land Stations. On all traverses, seismic and gravity measurements were made. Altitudes for gravity corrections were obtained barometrically. Two snowcats were used—while one was travelling, the second one monitored variations of pressure in one place thus allowing the true altitude changes to be determined from the readings made by the crew of the first vehicle. In the instance of one traverse of 1 600 miles length, closure error was only 2 m. This, however, is

more likely to be a coincidence rather than an indication of overall accuracy. After the variation of velocity with ice thickness had been determined, experimental results could be interpreted. Results indicate that there is an average of 3 000 m of ice over the rock surface. Much of Marie Byrd Land seems to be an archipelago which would not rise above sea level even if the ice sheet was removed. Free air gravity anomalies suggest that there has been considerable crustal flexure beneath the ice load with as yet only incomplete isostatic compensation. By combining the seismic and gravity measurements it was possible to determine the configuration of the underlying rock floor in considerable detail. In general there was a good agreement between the two methods except on the fourth leg of the Marie Byrd traverse. This discrepancy between the seismic and gravity profiles might be due to a sea channel between the ice and the rock surface, for which there is some geological evidence. In the course of the gravity survey Scott's gravity station was reoccupied and the reading obtained agreed within 1 mgal with the value given by Wright, the physicist on Scott's expedition.

The third I.G.Y. paper by *G. P. Woollard, J. C. Rose* and *B. C. Browne* dealt with pendulum measurements along geodetic arcs. The agreement between the Gulf quartz and Cambridge invar pendulums is so good that it could be stated with some confidence that gravity values given for arcs which have been checked independently with both pendulums, are close to the true values. Details of the latest measurements with the Cambridge apparatus on the Oslo to Johannesburg line were described in detail. It was pointed out that the discrepancy between Cambridge and Gulf values was almost constant at 0·75 mgal and probably indicated an error in the reference value assumed for two surveys, rather than a genuine difference in readings of the two pendulums. During the discussion of the behaviour of the invar pendulums it was mentioned that periods of all pendulums were slightly shorter after the trip, indicating a shortening of the length. While for a number of years the drift of pendulums was steady, the period increasing at about 1 mgal per year, this reverse tendency, which had been noticed for the past 18 months, was rather difficult to explain. Similar erratic behaviour of drift was noticed with the Gulf quartz pendulums.

An afternoon session was devoted to a symposium on "The Use of Borehole Data in Geophysical Exploration". The first paper, by *A. E. Levanto* described a three-component fluxgate magnetometer developed in Finland. The instrument was designed for use in 1·5 in. holes and had an outside diameter of 32 mm. The instrument is used for delineating lens-type ore bodies in an existing iron ore mine and has an accuracy of 0·3 per cent with a range of 0·6 gauss. Measurements are made every 2·5 m in the drill hole and to date 20 000 measurements have been made.

In the second paper, *D. W. N. Dolbear* discussed design requirements for a borehole gravity meter. The range required, 450 mgal, combined with severe conditions of high ambient temperature and pressure, strong temperature gradients and space limitations, excluded any present surface gravity meter from borehole application. The only instrument to reach testing stage was R. L. G. Gilbert's dynamic gravity meter but initial results were inconclusive and the instrument was never fully developed. Though requirements were severe and no instrument at present could be adapted for borehole use, the speaker felt quite confident that an instrument specially designed for borehole applications was a possibility.

The next three papers dealt with seismic exploration in boreholes. *S. M. Wyrobek* discussed interval velocity determinations in the English Trias, Permian

and Carboniferous. The intervals considered were of a mean thickness of 500 ft. While Bunter and Permian displayed changes associated with the region concerned, velocities of other formations appeared so far to be a function of depth independent of location. However, it was dangerous as yet to try to generalize about the results.

W. Holste described a refraction seismic method using a borehole geophone to determine the shape of salt-flanks and other boundary surfaces. Provided that a precise knowledge of the seismic velocities of all media involved was available, good practical results could be secured.

Lastly, *Ph. Dunoyer* and *J. Laherrere* discussed the application of the continuous velocity log to anisotropy measurements in the Northern Sahara. Measurements were carried out in two wells in order to obtain data to improve the interpretation of seismic refractions. They were based on the observation of the shortening of experimental oblique travel-times with respect to theoretical travel-times computed by not taking into account anisotropy. Since a detailed knowledge of the velocity distribution was required in order to eliminate all influence of refractions, a continuous velocity log was indispensable. The results from the two wells were in agreement and showed that anisotropy is essentially a function of lithology independent of either depth or age. If this result could be confirmed in general, then an anisotropy factor could be assigned to different layers by inspection of the geological log alone. The authors stressed that neglecting anisotropy might introduce errors of up to 9 per cent on depth determinations and more than 50 per cent on offsets.

M. P. H. Bott described the use of electronic digital computers for the evaluation of gravity terrain corrections. The development of a grid and an approximate formula suitable for programming was outlined. The corrections computed for 10 stations in the Arran survey were up to 5 per cent in error compared with the zone chart method. Using a medium speed computer a station can be reduced in about 14 s which means at present a cost of three shillings.

The only mention of airborne techniques was made in connection with a paper by *M. Reford* discussing irregular diurnal magnetic variations and their effect on the operation and the results of aeromagnetic surveys. These variations could be very severe in high magnetic latitudes like Canada. Preliminary results of experimental observations of these variations by means of pairs of monitoring stations up to 160 miles apart were reported. The problem was complicated by the fact that observed variations at two stations did not agree, probably due to differences in local geological formations (depth to basement) and difference in distance from the auroral zone. Besides, there was a constant change of phase between records at two stations. As a more profound knowledge of the phenomena involved was developed, it was hoped that a method for correcting airborne magnetic records for diurnal magnetic variations would be available. At present, an estimate of accuracy of the airborne data was possible from analysis of ground stations' records.

Of several papers that dealt with particular case histories and interpretation problems and certain instrumental refinements one by *J. Loeb* deserves mention for its originality of approach. In dealing with characteristic impedances in electromagnetic prospecting methods, the analogy between transmission line theory in electrical engineering and propagation of electromagnetic waves in stratified, non-magnetic, homogeneous conductive media was established and used to show under what conditions the knowledge of the surface field would give the thicknesses and conductivities of intermediate layers.

The increasing popularity of the E.A.E.G. was shown by the record attendance at this meeting, but in some respects it was disappointing that the emphasis was on what might be called "classical" exploration geophysics, over one-third of the papers dealing with seismic methods alone. While the papers were extremely interesting and generally of a very high calibre, it was felt that it would have been beneficial to all present if some mention had been made of the more advanced methods of prospecting. The electromagnetic method was neglected and very little mention was made of airborne techniques. In particular it would have been interesting to hear about the recently announced AFMAG method, and progress in research on synthetic seismograms.

The next meeting of the Association will be held at Munich in 1959 on 13, 14 and 15 May.

Book Reviews

Contributions in Geophysics in Honor of Beno Gutenberg

Edited by H. Benioff, M. Ewing, B. F. Howell and F. Press

(Pergamon Press, 1958, 244 pp., 60*s*.)

The Editors of this Festschrift have rescued a series of papers from appearing in journals and issued them in more permanent form, in honour of Dr Gutenberg on his retirement. No photograph—certainly not the poor one in the frontispiece—can convey his charm, shrewdness and gentleness, which many geophysicists were able to see at the 1957 Toronto meeting of U.G.G.I., where he played a prominent part, setting his younger colleagues an example of industry, accuracy and conciseness.

"Seismic Body Waves and Surface Waves" by M. Båth was given in Toronto. It is concerned with the proportions of the total energy liberated in an earthquake which go into the *P*-wave, *S*-wave, and surface waves, and gives formulae relating them to the earthquake magnitude (as defined by Richter & others). Also heard at Toronto was "Energy in earthquakes as computed from geodetic observations" by P. Byerly and J. De Noyer. They develop a theory for the elastic energy released by a faulting process, and then, using the results of triangulations done in earthquake regions before and after a big shock, calculate the extent of the faulting and hence the energy released. They conclude, for instance, that the great San Francisco shock of 1906 released $0{\cdot}9 \times 10^{23}$ ergs.

Another paper heard at Toronto was "The Free Oscillations of the Earth" by C. L. Pekeris and H. Jarosch. They give a theoretical treatment of the free oscillations of the Earth and give numerical results of the periods of such oscillations for different earth models. An approximate method, for Bullen's Earth model *B*, gives a period of 53 minutes, (given wrongly in Table 2 on p. 191, but rightly in the text below it). This is close to the period of the well known oscillation noted by Benioff in records of the Kamchatka shock of 1952 (57 minutes) and supports his suggestion that this oscillation was a free oscillation of the Earth as a whole. (It is a pity that the answer obtained by numerical integration for Bullen's model *B*, announced at Toronto, has not been incorporated in the book. It is 55 minutes.)

There is an interesting paper by R. Stoneley, giving an extension to Love waves of his recent theoretical and numerical work on Rayleigh waves. Then a useful survey by K. E. Bullen of the present state of knowledge about the inner solid core of the Earth. He shows that there is plenty of evidence for its existence, even though the critical phase *PKJKP* has never yet been found in seismograms, and hopes that work in theoretical physics on matter at high temperatures and pressures may help to decide if the boundary is sharp, or gradual.

Miss Lehmann gives a detailed study of earthquake records at distances of 105° to 115°. This region is of particular interest because of the *P* shadow zone which starts at 105°. She finds that *P* can often be read well right through this

region, and so the shadow zone does not have a sharp boundary. This detailed study, and others like it, are of great value in helping one appreciate the exact way in which the character of a seismogram varies with distance, in checking the accuracy of the travel-time tables, and in finding regional variations of travel-times. C. Tsuboi gives a detailed study of the seismicity of Japan, and, by finding the correlation coefficients between the numbers of earthquakes in each year in several small regions, shows that several "earthquake provinces" can be distinguished in Japan. These are regions, 100 km or so across, in all parts of which the seismicities in different years fluctuate together, more or less. He also mentions some work of T. Asada, whereby the general seismicity of a place can be estimated by observing the number of small shocks (of magnitude as low as -1) which take place in a period of only a few hours. Professor Caloi gives details of the fluctuations of tilt in a seismic region before and after a shock, and finds these to confirm Ishimoto's hypothesis that shocks may be caused by magma intrusion (rather than faulting).

There are other papers dealing with general earthquakes mechanism (and the "rotating Pacific" theory), fault plane studies, explosion seismology and the structure of the crust, special seismographs for lowering down deep wells, laboratory work on rocks at high temperatures and pressures (F. Birch shows that this can explain the *Lg* channel wave), the formation of geosynclines, gravity formulae, data processing, and magnetic coupling between the solid mantle and the liquid core.

Most of the subjects which have interested Dr Gutenberg are thus touched on in this book. Not all: that would have needed a new "Handbuch der Geophysik". There is nothing on microseisms, for instance, or the correlation of simultaneous records made at neighbouring stations. But in general this book indicates how widely Dr Gutenberg's fertile scientific imagination has ranged in seismology; indeed this book might serve as a general survey of the state of modern seismology. It is a pity that the Editors themselves did not contribute: a paper by Professors Ewing and Press on their important work on surface wave dispersion and crustal structure, and a paper by Professor Benioff on modern instrumentation, would have made the book's range more complete. This well-produced volume is the first in the Pergamon Press's "International Series of Monographs on Earth Sciences". Let us hope it will include many books of such interest and value as this one.

N. A. Routledge.

Polar Atmosphere Symposium, Part I: Meteorology Section

(Symposium at Oslo, 2–8 July, 1956)

Editor R. C. Sutcliffe

(Pergamon Press 1958, 340 pp., 70*s*.)

This volume is a collection of the contributions to a symposium made by a number of leading meteorologists. The topics include the geography and climate of the arctic, sea ice and its prediction, radiation and temperature near the ice,

and the wind flow and temperature structure of the Arctic troposphere and stratosphere. The recent special expeditions into the Arctic and the extension of the routine weather-observing network towards the pole, give the authors a more satisfactory basis of facts than has ever before been available: the exploratory era is almost past, and the problems of polar meteorology appear to have been brought practically to a par with those of middle-latitude meteorology, where the basic complexity of the processes and not the lack of data is the main impediment to progress. It is interesting to find one writer complaining that observations are not published in convenient or indeed in any form ("what are needed are processing facilities and accessibility to observations already stored and unused in our archives"), for this is a nuisance which plagues even the student of European weather, and whose removal deserves the efforts of pioneers with the spirit of the arctic explorers.

Generally the papers in this volume have a high quality, which might well be expected from the authors and its eminent editor, who it must be supposed is responsible for the unusual coherence and therefore value of the summaries of the discussions following each group of papers. The book is handsomely produced, in the publisher's usual manner, and at a price which seems not unreasonable.

F. H. L.

Annals of the International Geophysical Year, Vol. VI

Ed. L. V. Berkner

(Pergamon Press, 1958, 508 pp, £6)

The full title of Volume VI of the Annals of the International Geophysical Year is "Manual on Rockets and Satellites". It may seem strange that a manual for observers should be published at the close of the intended period of observation; but this is surely a measure of the vitality of the IGY and of the necessity for continued international co-operation and planning in many branches of geophysical and astronomical research.

The use and interest of this volume will outlast the IGY by many years in spite of the youth and startlingly rapid growth of the techniques it covers. Sections have been contributed by each country using rockets as a means of research, describing the types of experiments being carried out and the frequency of launchings planned. The section on satellites contains 100 pages of general information on satellites, orbit theory, perturbations and drag effects, as well as tables and nomograms useful in predictions of satellite position and visibility. This is followed by detailed descriptions of the original satellites and experiments planned by the USSR and the USA, and also of the arrangements which have been made for tracking and collection of data from the satellites. The part played by new launching activities is also briefly described. A final section containing the resolutions passed at the various CSAGI conferences gives useful information on the methods planned for the transmission of information and coordination of experiments of a world-wide scale, and the volume ends with a brief description of the first two satellites launched by both the USSR and the USA.

Inevitably some of the information contained in the 500 pages of this book became out of date as soon as a satellite was launched, but most is of enduring value to all interested in the larger aspects of geophysical research, and Dr Berkner and his editorial colleagues are to be congratulated on assembling so much and such varied data in a very short space of time.

J.G.D.

Classical Mechanics

J. W. Leech

"Monographs on Physical Subjects", Methuen, (1958, 149 pp + ix, 12*s*. 6*d*.)

This little book is a welcome addition to Methuen's well-known series of Monographs on Physical Subjects. It gives a clear and concise account of classical mechanics, dealing with the Lagrangian and Hamiltonian formulations, variational principles, transformation theory, Poisson brackets, continuous systems, relativistic mechanics and field theory. The author's object is to prepare the ground for the study of quantum mechanics but the basic theory for a number of geophysical problems, such as those connected with normal modes of vibration and the relation between geometrical and wave mechanics, will be found clearly set out. A general familiarity with the topics of this book will in fact be found useful in many problems in geodesy and geophysics as well as those ordinarily treated by these methods, and this book provides a clear and terse introduction to the subject. There is a useful bibliography.

A.H.C.

ERRATA

Geophys. J., **1**, No. 3, 1958:

Hugo Benioff and Frank Press, *Progress report on long period seismographs*, p. 210

Figure 2 is mis-set, and should appear as follows:

FIG. 2.—Mantle and crustal Rayleigh waves showing impulsive initiation corresponding to maximum value of group velocity. Loyalty Islands earthquake of 1956 November 26, magnitude 6¾. Upper trace Press-Ewing Z, $T_0 = 30$ s, $T_g = 90$ s; lower trace Benioff Z, $T_0 = 2$ s, $T_g = 180$ s, 100 mF shunt, $CRDX = 130\,000$ ohms.

Geophys. J., **1**, No. 4, 1958:

A. H. Cook, *Determination of the Earth's gravitational potential from observations of Sputnik* 2 (1957β), p. 344

In Table 1, second line, *for* $\pm 38{\cdot}2$ *read* $\pm 8{\cdot}2$.

РЕЗЮМЕДОКЛАДОВ, В ПЕРЕВОДЕ НА РУССКИЙ ЯЗЫК

НАПРАВЛЕНИЯ ИНТЕНСИВНЫХ ГЕОМАГНИТНЫХ КОЛЕБАНИЙ

В. Д. Паркинсон

На большинстве станций умеренного пояса векторы, обозначающие геомагнитные измерения в промежутках времени короче одного часа, расположены в одной плоскости. Во многих случаях эта плоскость почти горизонтальна, но иногда она наклонена под большим углом. Повидимому это является результатом вихревых токов, несиметрично индуктированных в Земле и вероятно образующихся благодаря сильной проводимости океанов.

ПРИЗНАКИ ПРОМЕЖУТОЧНОГО СЛОЯ ИЗ ИЗУЧЕНИЯ СТРУКТУРЫ ЗЕМНОЙ КОРЫ В ЮЖНОМ ТРАНСВААЛЕ

А. Л. Хейльс и И. С. Сакс

В этой статье описываются наблюдения над временем прохождения волн Уитуотерстрэндского землетрясения, следующих через Восточный Трансваал. Самым удовлетворительным объяснением считается представление, что земная кора состоит из двух прослоек. Скорости волн P и S в гранитной прослойке соответственно 6,0 и 3,6 км/сек. В промежуточном слое скорость P между 6,7 и 7,2 км/сек, а скорость S — между 3,95 и 4,15 км/сек. Скорость P_n оказалась 7,96 км/сек, а толщина земной коры 36,6 км.

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Роберт Б. Харгривс и Альфред Г. Фишер

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Geophysical Journal

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2. Papers should be typewritten with double spacing and on one side of the paper only. Wide margins, at least 3cm, should be maintained. All pages must be numbered consecutively; manuscripts are not required for Letters to the Editors.

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6. Authors should read carefully proofs submitted to them and should return them promptly. Any alterations other than the correction of misprints may be charged to the author.

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